

QC929
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U. S. DEPARTMENT OF AGRICULTURE
FOREST SERVICE

ALTA AVALANCHE STUDY CENTER
WASATCH NATIONAL FOREST

Translation No. 2

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Publication
Section ..
Sept. 1974*

ON THE DESTRUCTIVE FORCE OF AVALANCHES

by

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Ueber die Zerstoerungskraft von Lawinen

Schweizerische Bauzeitung

1955

Translated by R. E. Tate
March 1964

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This photograph was reproduced and kindly placed at our disposition by the AEEM, Association des Entrepreneurs du Barrage de Mauvoisin, (Association of Dam Contractors of Mauvoisin). An avalanche released on a rock ridge (about 2500 m above sea level) shoots over the rock slope of 47° average inclination into the gorge and climbs again on the opposite side ($\sim 36^{\circ}$) to about 2000 m (Elevation of the structure in this picture is about 1960 m above sea level).

The avalanche catastrophies of the past years have caused various devastating effects in places where, within the memory of man, no destructive avalanches have occurred [1, 2]. Repeatedly the question arises under what conditions and to what extent are the homesteads, structures, and cultures of the mountain regions imperiled and what construction measures can offer protection against the destructive effect of avalanches.

As to constructions to prevent the formation of avalanches, fundamental work has been carried out in Switzerland [3 to 8]; it is however, practically impossible to obstruct all possible destructive avalanche catchment basins within a reasonable time and it remains necessary to protect certain buildings directly by means of structures or to construct new buildings (for example power stations) in such a way that they withstand the action of avalanches.

The prerequisite for a solution to these problems is a knowledge of the forces occurring in avalanches in the case of particular situations. The object of the following details is to gain an insight into this matter. These are based upon domestic and foreign observations; here, however, only the determinations made in the Vorarlberg in 1954 will be gone into in detail, since there the most important data could be collected shortly after the catastrophe. On the other hand these observations are especially interesting, since until now such large and extensive destructive effects have been observed very seldom in a district with such slight slopes and the investigation of these cases will throw some light on the lower limits of the effects of avalanches. Swiss experience is referred to only in section IV, where substantially larger forces were noted than in the Vorarlberg; these larger forces being observed in only a few cases. For the rest one may refer to the detailed Berichte des SLF [1] (Reports of the Institute for Snow and Avalanche Research).

In agreement with the pioneering domestic and foreign practice this report closes with an attempt to establish a highly simplified avalanche dynamics, which strives for a more qualitative analysis of the effects of the most important factors and may serve as a suggestion and working hypothesis for further observations and investigations.



Avalanche in the Karakoram (Golden Throne)

I. ESTIMATION OF THE FORCES OF AVALANCHES FROM THEIR EFFECTS.

Immediately after the avalanche catastrophe, which in January of 1954 had overrun the Vorarlberg, the firm Vobag AG., Adliswil, commissioned the EMPA to survey the specific instances of damage, with the objective of obtaining inferences as to the magnitude and direction of the forces operative during the impact of avalanches on obstacles and under the existing circumstances. The analyses were based predominantly upon building damage, in the evaluation of which, the structural engineering experience of the EMPA could be drawn upon. In accordance with the wishes of R. Tschudi, Director of Vobag AG., the knowledge collected and the conclusions drawn therefrom by the observers are reported below. The inspections and surveys, which took place on the 19th and 20th of February and the 2nd of March and their evaluation have been the concern, on behalf of the EMPA, especially of the technical expert, W. Rimathé, in addition to the author.

1. General Information

Concerning the snow situation which led to the catastrophe, Forest Engineer Brantner, avalanche adviser for the Bludenz district construction authority for torrent and avalanche control, expressed himself as follows: "Since New Year's low temperatures had retarded a thorough consolidation of the snow cover deposited since 19 December. On 8 January its structure still was characterized by a very weak base layer and zones of loose or wind packed surface layers. On this base, between 9 and 12 January, up to 160 cm of new snow fell with stormy, snow-laden northwest winds. With rising temperature these enormous masses slid, mainly as loose snow avalanches for lack of cohesion to the existing base layer. Unfortunately, I am able to report only limiting values for the snow density. The density was between about 50 to 150 kg/m³. Also I can report only a little information about the velocities and I can give you only indicative numbers. They might have moved between 20 and 60 meters/sec."

The details from eyewitness observations concerning the catastrophe are unreliable; because of darkness, restricted visibility and snowfall exact observations were not possible. According to the statements of Councilor Wagner in Bregenz, the release zones are not clearly determinable; nevertheless releases, evidently triggered by snowfall, may have occurred even in the timber and produced avalanches. In any case it has been established by the investigation that the avalanche ran through forest with relatively thick underbrush (for example in Bings). Objective measurements to characterize the snow at the time of the catastrophe were not obtained later. Snow with very little cohesion was probably present at the time of the catastrophe.

Figure 1 shows the terrain near Blons and gives a summary of the avalanche situation. The average slope is estimated to be about 30°. The slope of the zone of origin and fracture behind the Dalaas railstation is pictured in Figures 2 and 3. In view of the prevailing meteorological situation on the occasion of the avalanche catastrophe in the Vorarlberg it may be assumed that the snow conditions in the Dalaas district did not differ materially from those in the Gross-Walsertal.

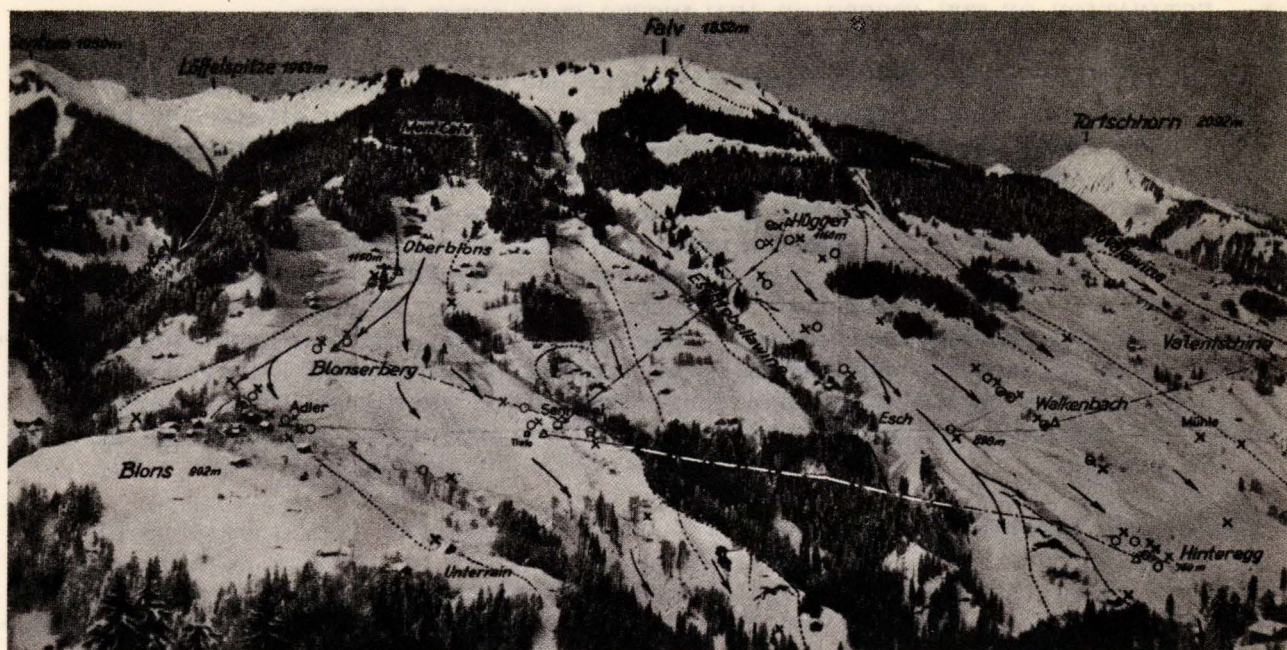


Fig. 1. Avalanche paths in the Grosse Valsertal on 11 January 1954. O destroyed houses, X destroyed stables, Δ cable railway stations, — . — . — cable railways, ———— direction of the slides, ... boundary of the avalanches.

2. Determinations from Destroyed Objects

A. Blons and Sonntag

The houses which were destroyed in Blons and Sonntag were of a similar type of construction: they had been built of wood on a masonry foundation, either of sawed log or of frame and siding construction. The log houses were in many cases covered with wooden shingles. The destruction will be indicated by some typical examples described below.

a) Mesmerhaus in Blons (Figure 4; Table 1)

The house, of log construction, was raised off its foundation by an avalanche, pushed along in its entirety about 50 meters, and stopped inclined on a lateral slope. As a secondary result, due to the sloping position, the upper story with the roof slid off horizontally from the remainder of the structure. The rear wall of the building was pushed in up to a height of 2.5 meters, while the higher gable wall, although very much weakened by window openings, disintegrated, without the logs being broken. No additional exact clues concerning the original construction of the pushed in part of the wall exist. The width of the wall was about 6 meters and the thickness of the logs was 17 to 18 centimeters. It is to be expected that this part of the wall was also weakened by window and door openings. Assuming a wall without openings and a buckling strength of about 400 kg/cm^2 for the existing timbers, a calculated static pressure of a maximum of about 4500 kg/m^2 is required to break the wooden timbers.

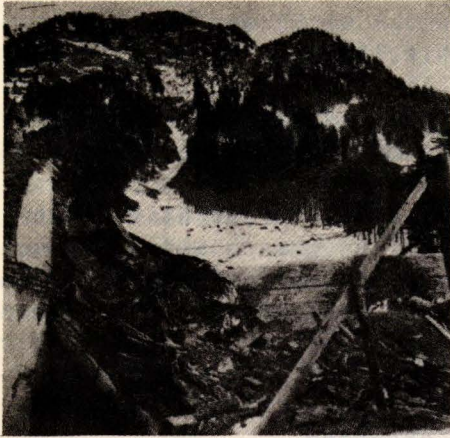


Fig. 2. (Left) View toward the avalanche path above the Dalaas rail station.

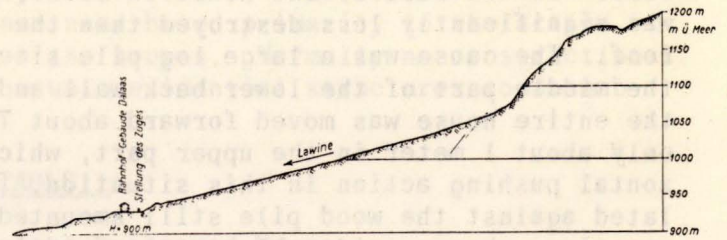


Fig. 3. Longitudinal profile of the avalanche path above the Dalaas rail station (Arlberg line), scale 1:8000.

Ordinate -- meters above sealevel. Lawine -- avalanche. Bahnhof-Gebäude Dalass -- Rail station building Dalaas. Stellung des Zuges -- position of the train.

Because of the existence of openings in the wall, its strength is very much reduced, so that the buckling strength of the timbers no longer is the determining factor, but the forces must be absorbed by the tenons of the vertical beams. The given pressure is to be considered therefore as the upper limit, which probably was at most only halfway reached. From the established destruction, as well as from the existence of intact window panes in the front and side walls, it is concluded that upon the striking of the avalanche no impact stresses occurred. On the contrary, the events must have started so slowly that they may be calculated as static compressive load. The destruction of the back gable wall and of the roof sheathing indicates an upward acting component of force. With the house furnishings and the snow load, without the foundation, the weight of the house would be estimated at between 40 and 50 tons. For tipping about the leading edge, a vertical force of about 20 to 25 tons was thus necessary, which would correspond to an upwards directed component of force on the rear facade surface of about 650 to 750 kg/m².

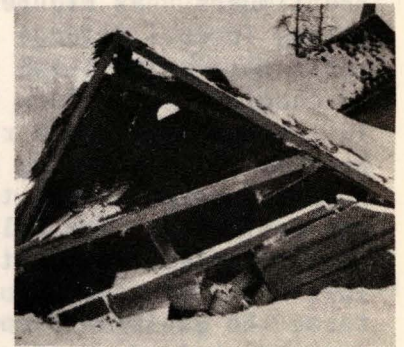
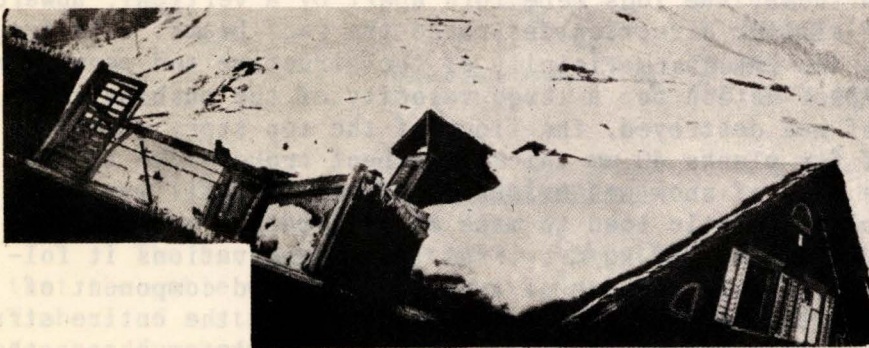


Fig. 4. Mesmerhouse in Blons. The house, of log construction, was raised in its entirety from the foundation, moved to a side slope where, as a result of the sloping position, the upper story slid off from the rest of the house. At the right the building wall facing the avalanche.

b) Dwelling House in Sonntag (Figure 5; Table 1)

The construction of the house was practically the same as that of the Mesmer house in Blons; the gradient of the avalanche path was probably somewhat less. In contrast to the house in Blons, here the lower part of the back wall was significantly less destroyed than the gable wall and the rear half of the roof. The cause was a large log pile situated behind the house, which protected the middle part of the lower back wall and acted as a deflecting wedge. Although the entire house was moved forward about 7 meters, the wood pile moved forward only about 1 meter in the upper part, which indicates a relatively smaller horizontal pushing action in this situation. The length of the snow wedge accumulated against the wood pile still amounted to about 7 meters at the time of inspection, when considerable settlement already had occurred.

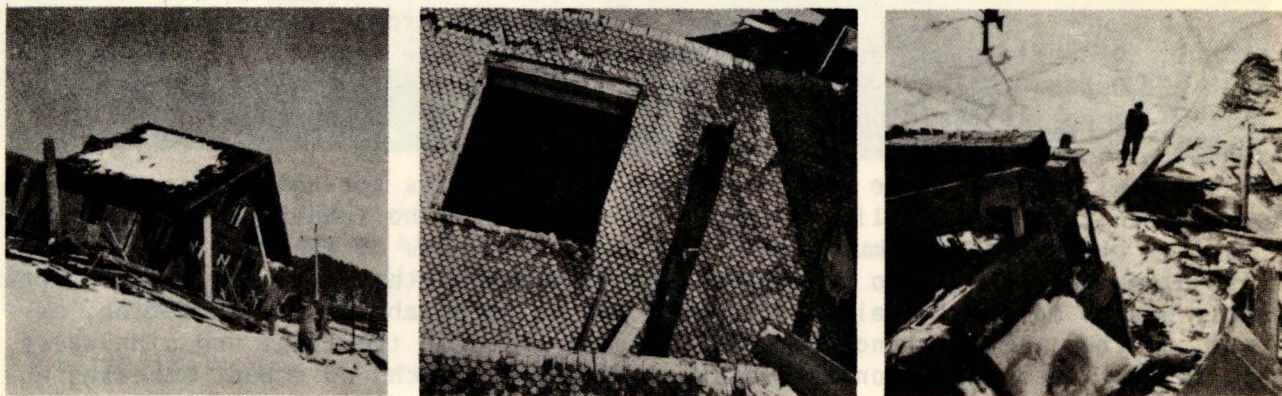


Fig. 5. House in Sonntag Left: Portion of the front structure pushed and tipped forward. In the Center: Portion of the side wall of the rear part of the structure with lifted and thrown off timbers. The beam over the window is also raised. Right: Detail of the rear corner showing mortise-and-tenon joint lifted apart.,

The destruction of the gable wall is not attributed to bending failures of the timbers. As Figure 5 shows, the logs were torn apart by a vertical, upward acting force. A force of similar direction destroyed the roof beams. The fragments were still lying in the immediate vicinity of the structure and permit one to conclude neither an impact action nor a large velocity of the pushing snow. In the zone where the roof was destroyed, the floor of the top story, 5 meters by 4 meters consisting of fir planks 40 mm thick, was bent trough-like to the breaking point, where the mass of snow was evidently dammed up until the roof was destroyed. The calculated static load to make an indentation on the floor of the top story amounts to 300 to 350 kg/m². From these observations it follows that, in time sequence, first, because of a vertical upward component of force the gable wall and a part of the roof were destroyed and the entire structure was raised at the rear from the foundation, and then in a later phase, the whole house slid forward because of the dammed up mass of snow. To raise the house on one side a vertical force of about 30 to 35 tons (approximately 0.7 tons/m² on the facade surface) was necessary, which corresponds to the order of

magnitude of the force necessary to break the roof beams from below, while to shove the house after lifting (with a coefficient of friction on snow $\mu \sim 0.2$) only about 15 tons was sufficient, which corresponds to about 800 kg/m^2 on the rear surface of the building. The estimated calculation of the two cases in Blons and Sonntag show first, satisfactory agreement in the magnitude of the effective forces, and second, relatively small forces. The severe destructive actions which nevertheless occurred are attributed primarily to the action of upward directed components of force on the houses. Normally no constructional preventive measures are taken in the usual residential structures to absorb these (upward) forces.

TABLE 1

Principal Data on the Destroyed Houses
(Data are approximate)

		House in Blons	House in Sonntag
Width	meters	6	10
Length	meters	8	10
Height of first story	meters	2.5	2.5
Height of gable wall	meters	4	4
Wall thickness (without shingles)	centimeters	17-18	16
Roof area	square meters	100	180
Weight, estimated	metric tons	40-50	60-70
Force to raise one side including the snow load	metric tons	20-25	30-35
Upward thrust per square meter of wall	kg/m^2	650-750	700-800

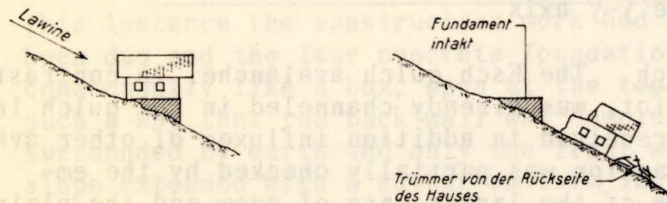


Fig. 6. Schematic representation of the destruction process of houses in Blons (Fig. 4) and Sonntag (Fig. 5) before and after the catastrophe. Lawine -- avalanche, Fundament intakt -- foundation intact, Trümmer von der Rückseite des Hauses -- Debris from the back side of the house.

c) House and Stable "Walkenbach"

The house was of frame construction and was built deep in the slope, so that the gable wall on the mountain side rose only 2 or 3 meters over the ground. Timbers of a stable located higher had been carried onto the roof by an avalanche; furthermore, the structure of a cable railway station located immediately nearby was torn away. In spite of the light construction, the house sustained no external damages worthy of mention except for a small displacement towards

the valley. On the gable wall individual timbers were close to the breaking point. Because of the small exposed surface the upward acting component of force could not take effect sufficiently. The pressure, at most about 3000 kg/m^2 (estimated from the damages observed in the timbers), of the snow mass on the relatively little exposed gable wall on the mountain side was insufficient to tip the house forward.

d) Other Objects

Concrete foundations of cable railway stations. The foundations had been constructed as concrete cells as shown in Figure 7. The foundation depth on the side toward the mountain varied according to the gradient of the slope. Although the wooden superstructure was destroyed at the time, none of the foundations inspected were displaced by the avalanches. The calculated tipping stresses must have been smaller than 4000 to 5000 kg/m^2 .

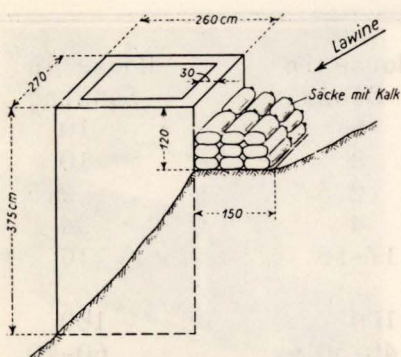


Fig. 7. Cable railway foundation in Blons. Lawine -- avalanche, Sacke mit Kalk -- sacks of lime

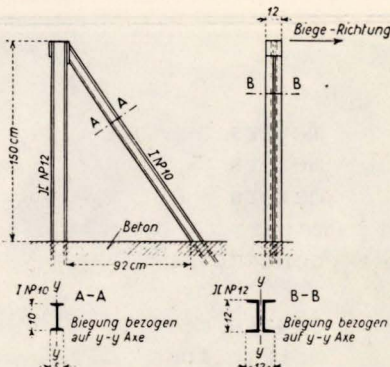


Fig. 8. Structural steel support for the cable railway in Blons. Biege-Richtung -- Bending direction, Beton -- concrete, Biegung bezogen auf y-y Axe -- Bending about the y-y axis.

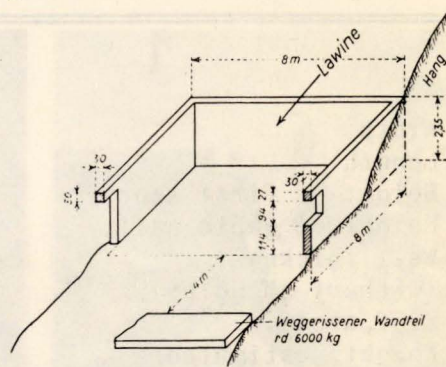


Fig. 9. Foundation wall of a new structure in Blons. Lawine -- avalanche, Hang -- slope, Weggerissener Wandteil rd 6000 kg -- Part of the wall torn away, about 6000 kg.

Handrail post in the Esch gulch. The Esch gulch avalanche, in contrast to the other avalanches in this district, was already channeled in the gulch in the "release zone" and in descending received in addition influxes of other avalanches from the side. Also, the expansion was partially checked by the embankment on the side, so that, because of the larger mass of snow and the plainly greater snow load, the nature of this avalanche lies between the powder avalanches and the ground avalanches (Grundlawine)*. This conclusion is also indicated by the damages which occurred in the forest stand along the edge of the gulch, as opposed to the barely detectable damages in a stand of timber from a powder avalanche in Bings-Blundenz. The path of the avalanche in Bings ran thru a forest on a steep rocky slope. In spite of the fact that a building at the transition of the slope to the level was destroyed by the avalanche in the

* Translators Note: Grundlawine -- an avalanche to ground, usually with stones, earth, etc., entrained.

usual manner, only insignificant damage occurred in the stand of trees. A further difference compared with the other avalanches lay in the composition of the snow mass. In the Esch gulch the snow was mixed rather uniformly throughout the entire depth with wood fragments, earth, and stones, while in the other avalanches, in spite of very large snow depth in some cases, for example, in the dammed up zone at the Dalaas rail station, the debris lay localized at the time in the vicinity of the destroyed objects or spread at a certain distance on the surface of the snow. These observations permit one to conclude that, in this "channeled" avalanche, the pushing effects were materially greater than in loose snow avalanches sliding on an open slope. This avalanche may be considered to be the one with the greatest forces in that region under the existing conditions. Indicators for the limits of the forces are, first, a piece of railroad rail, which served as a post for a handrail and remained intact, and consequently gives a limiting value which was not reached, and furthermore, broken off tree trunks, which indicate the lower boundary value that was exceeded. The static calculation shows that the stress of about 6000 kg/m^2 projected on a round timber was exceeded.

A structural steel support, shown in Figure 8, which had been erected for a projected cable way, the cable of which had not yet been installed, was bent over sideways. A static stress of about 3500 kg/m^2 is necessary to bend it in the direction shown, see Figure 8a.

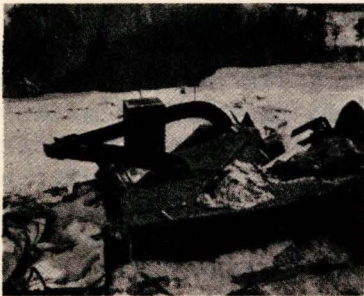


Fig.8a. Structural steel support bent down by the avalanche.

Foundation wall of a house under construction in Blons (Figure 9). In this instance the construction work had been stopped after the excavation had been dug and the four concrete foundation walls had been poured. The object was consequently like a box, open at the top, placed horizontally on the slope in such a way that the back wall was completely and the side-walls were partially surrounded by earth and only the front wall on the valley side stood free. The slope extended with a rather uniform inclination (about 30°) and without significant barriers more than 700 to 1000 meters upwards to the forest boundary. The concrete wall on the valley side was torn away from the side walls and turned over by the avalanche, but, in spite of the inclination of the slope, it was moved only about 4 meters. The calculated thrust to break away this wall, assuming a tensile strength of 15 to 20 kg/cm^2 for the concrete, amounts to a total of about 100 to 150 tons, corresponding to 3000 to 5000 kg/m^2 of wall area.

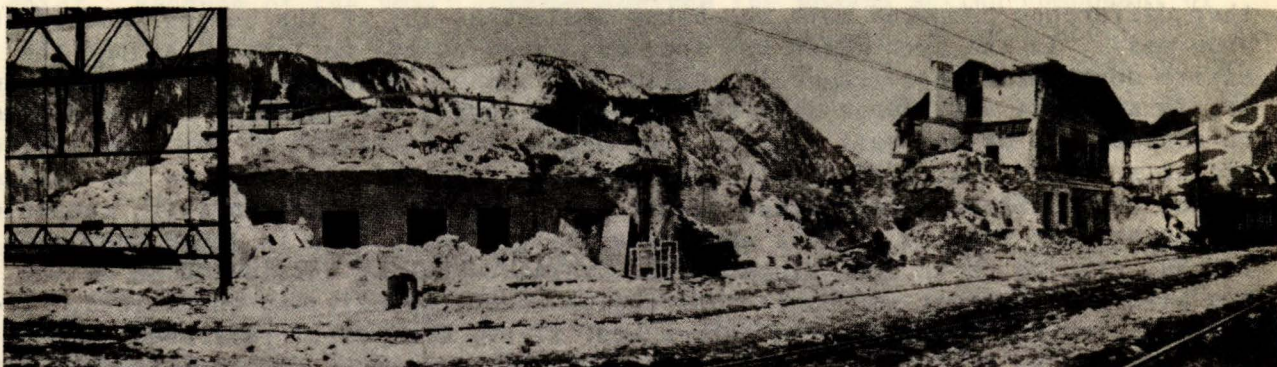


Fig. 10. Over all view of the destruction at the complex of buildings at the Dalaas rail station.

B. Dalaas Railroad Station

a) The Building

The general situation of the catastrophe of January 1954 is shown in Figure 3. The avalanche struck the front of the railway station building. The western part of the building, still standing, was about in the center of the avalanche. From the distances of objects still intact, the effective width of the avalanche can be estimated; it amounts to about 120 meters. In view of the flatness and width of the slope this small width is only understandable if one assumes that an avalanche, released from a steep collection zone located higher, penetrated the entire slope without expanding sideways. As a result of the damming action of the undestroyed part of the building, the height of the snow reached about 7 meters (Figure 11). The extent of the destruction of the building in general is visible in Figure 10. On the east side (left in Figure 10) the roof was removed, or tipped over toward the rear. The roof fragments lay immediately behind the structure. The lower part of the building, about 12 meters wide and 3.3 meters high, constructed of brick walls 40 centimeters thick, remained standing. Windows and doors together with the frames were pushed inwards. Based upon practical experience with explosive tests, pressures of the order of magnitude of 100 to 200 kg/m² are sufficient for these damages. The mass of snow pressed into the interior set up a cross pressure so that connecting doors on the side were crushed and ceilings were raised (Figure 12). In the case of the single story structure being discussed, because of insufficient wall pressure, obviously overcoming the shear strength is the determining factor for the pushing in of the front wall. Assuming a shear strength of 5 to 10 kg/cm² for the masonry, the pressure on the wall surface was 1200 to 2400 kg/m². Behind this part of the rail station building, at a distance of about 15 meters, was a house with a covered veranda. The veranda roof was crushed from above because the snow masses, dammed up by the building standing in front, plunged as if over a spillway onto the veranda roof behind. This force component acting predominantly downward from above is also indicated by the observation that the rest of the building front and even the window panes remained intact. The middle part of the railway station was completely caved in.

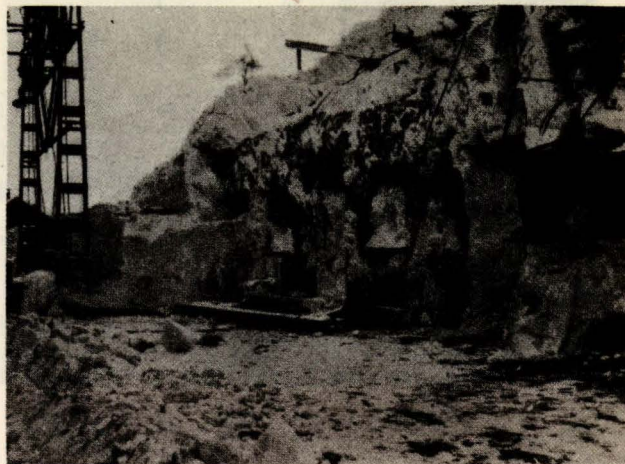
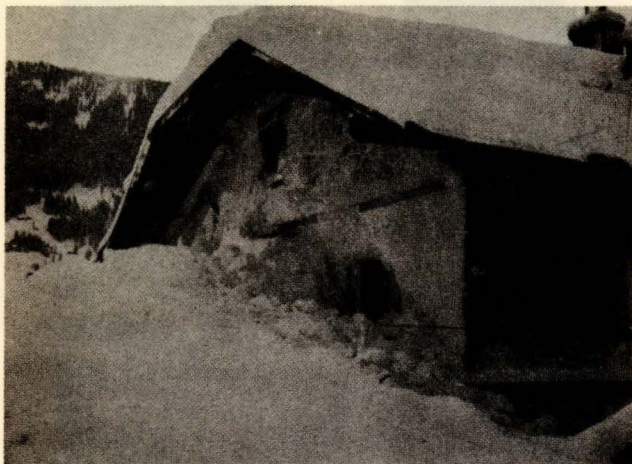


Fig. 11. Masses of snow dammed up to about 7 m height at the front side of the Dalaas rail station

Fig. 12. East part of the building with snow forced in at the door and window openings.

The western part of the building as well as a 3 to 4 meter structural steel tower located nearby remained standing, in spite of the fact that the snow was dammed up higher than the third floor. The pressure of the avalanche there could not have exceeded about 2000 kg/m^2 . An overturned electric locomotive, which was pushed in front of the building and thereby formed a protective wall 3 meters high, obviously prevented the collapse (Figure 13). The condition of the window shutters and windows in this part of the building is very instructive. Not only on the ground floor but also on the second floor were the shutters either intact or only slightly damaged. In the center window of the second floor even the window panes were still present. These observations permit one to conclude that the "pressure front" preceding the avalanche contained little energy. It must have struck the building wall before the locomotive was pushed in front of it.

The state of the fracture surface between the standing and destroyed parts, located crosswise to the building and consequently in the direction of the avalanche provides certain clues to the process of destruction, Figure 14. The brick partition wall was demolished only at the level of the second and third floors and only up to the central longitudinal wall. For these damages two actions of force are to be distinguished from the pictures of the fracture, namely, a shear force tending obliquely upwards in the direction of the partition, as evidenced from the direction of fracture of the existing beam and the twisting of the bricks in the fracture zone (Figure 14), and a cross pressure acting perpendicular to the wall surface.

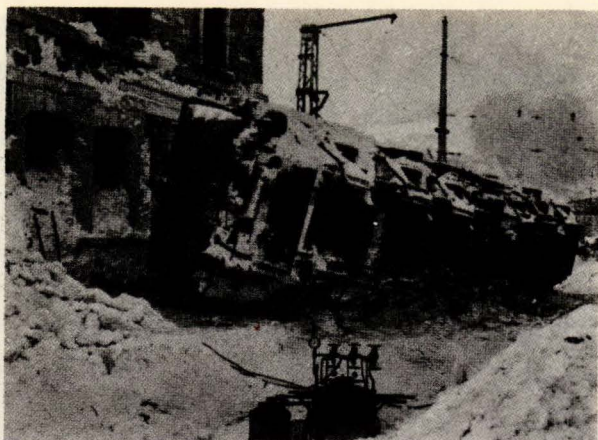


Fig. 13. West part of the building remaining standing (as in Fig. 11) with the locomotive lying in front, after clearing of snow.

The transverse force which demolished the brick wall being discussed, especially in consideration of the loosening of the bonding occurring as a result of the longitudinal force, could hardly have exceeded about 100 to 200 kg/m^2 . An estimate of the magnitude of the force component acting in the longitudinal direction is difficult, since details about the direction of the straining forces are not plainly obvious from the damages. Probably the wall was raised in front by a vertical component of the pressure and then caved in by a small pressure from the side. For this a vertical pressure component of 500 to 1000 kg/m^2 on the front wall of about 20 square meters of surface which caved in with the partition wall, was sufficient.

The part of the partition wall standing between the central longitudinal wall and the rear exterior wall was torn apart by shear. From the pattern and position of the gaps it is concluded that the thrust point of the horizontal acting force component struck rather high up, approximately at the floor of the second story.

b) Railroad Train

At the time of the catastrophe a railroad train, consisting of an electric locomotive and five, four-axled coaches, was standing in front of the Dalaas rail station. The locomotive was turned over by the avalanche and pushed in front of the station building. The coach following was likewise turned on its side, disconnected from the train, and then evidently pushed crosswise. From a gaping hole in the roof it was concluded that one end remained attached to an object (presumably a transmission tower), whereupon the coach turned 90° and then slid in the length-wise direction further down the slope. The second coach was likewise laid on its side and then further turned over onto its roof, pushed in front of the ramp of the freight shed, and finally raised, with the wheels upward, onto the 110 centimeter high ramp. The third coach was turned over on its side and pushed diagonally over the railroad yard. The remaining coaches remained undamaged. Figure 15 shows the details. Both the locomotive and the second coach were completely covered with the dammed up snow.



Fig. 14. Condition of the partition wall on the second floor. Direction of the avalanche from right to left.

For the event the following evidence is important: the sheet metal covering the exposed side of the locomotive was undamaged, just as the sides and window panes of the railway coaches on the side toward the avalanche were intact. It is concluded from this evidence that no shock load worthy of mentioning occurred when the avalanche front struck. According to testimony from the occupants of the first coach, which was transported the farthest, the incident took place very slowly. This testimony was verified by the nature of the injuries to the travelers, which generally were harmless and consisted mainly of scrapes and cuts, the last originating in part from breaking the windows to escape. The assumption previously deduced from the building damage at Blons, that the destructive process starts so slowly that the force actions can be estimated statically, has been verified by these statements.

To tip the locomotive weighing 120 tons, assuming a uniformly distributed force on its side, at least 51 tons or 850 kg/m^2 was required; to tip the coaches at least 18 tons or 300 kg/m^2 . Under the extreme assumption that the coach, after being tipped, was pushed onto the ramp and only then was raised by the snow pressing underneath, the lifting force would have amounted to at least 41 tons or 660 kg/m^2 . But, if it is assumed that the coach has been pushed or rolled on a snow cushion onto the ramp, which is indicated by the final position with the wheels upward, a force of from 400 to 500 kg/m^2 is necessary for raising it onto the ramp on the underlying snow wedge at an angle of 45° .

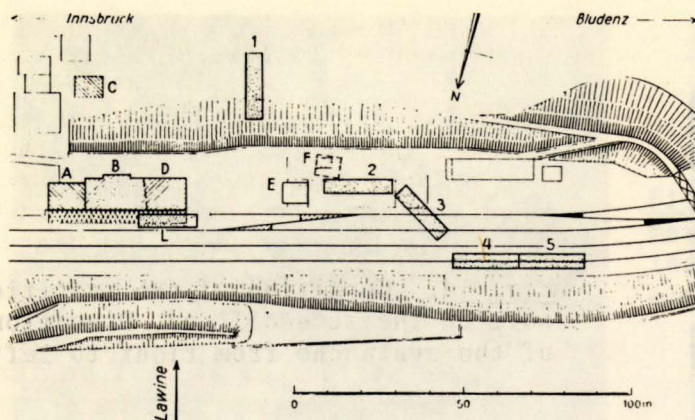


Fig. 15. Plan view of the Dalass rail station and the displaced train components, scale 1:2250.

- A. Totally buried emergency power supply unit.
- B. Totally destroyed part of the rail station.
- C. Crushed and deeply buried pig stall.
- D. Part of the building still standing.
- E. Freight warehouse pushed to F.
- L. Overturned locomotive 120 tons
- 1. Coach pushed down the slope.
- 2,3 Overturned coaches.
- 4,5 Coaches remaining on the track.

The forces for pushing the turned-over locomotive or coaches with the smooth metal surfaces on the powder snow are small and, assuming a coefficient of friction of 0.1 to 0.2, amount to about 200 to 400 kg/m² at most for the locomotive and about 70 to 140 kg/m² at most for the coaches. The facts that the part of the railway station building located behind the locomotive was not destroyed, that even the window shutters and windows in part remained intact, and that the light wooden shed located behind the second coach was only slightly pushed aside, permit the conclusion that, with the movement of these parts of the train, the avalanche was essentially stopped. The great dammed-up mass of snow also indicates this. The statically determined forces which were expended in bringing the avalanche to a standstill amount to about 1000 to 1200 kg/m² for the locomotive and about 700 to 1000 kg/m² for the railroad coach, depending on the hypothesis for the lifting process. From the magnitude of the forces determined, which occurred in the movements of the locomotive and coaches, the inclination of the effective resultants can be estimated to be 20 or 30 percent.

II. THE KIND AND MAGNITUDE OF THE OBSERVED PRESSURE EFFECTS.

The observed destructive effects may be summarized as follows:

1. The forces, which in the situations investigated, caused the damages in the avalanche path, originate from the resistance which the object presents to the flowing snow mass. The observations have shown that, in the cases investigated, the rise of the forces to the maximum value ensued relatively slowly. The effect on the objects must not be examined according to impact theory, but the forces acting can be explained according to static principles.

2. As a result of the flow process accompanying the damming of the snow, forces act upon the objects in the direction of flow of the avalanche, as well as diagonally, particularly upwards, in the course of which the pressure maxima of the various forces do not coincide in time. The resultant impact energy of the avalanche acts upwards as a rule, especially on slopes of small inclination and in ravines (Dalaas, Monstein), but it also can act downwards below very steep slopes (Vals). In the cases investigated the pressure effect in the thrust direction of the avalanches seldom exceeded 5 tons/m² on the surface of the object struck, where it was principally a question of loose snow or powder avalanches. Only in three special cases in Switzerland was it concluded that the maximum pressure effects were from 10 to 20 tons/m², where it was a question of steep slope inclination, 45 to 100%, and in part of ground avalanches (Grundlawinen).

The vertical forces, occurring as a result of the damming of an avalanche by an obstruction in the slide path, can, in the normal design of houses, reach about half the value of the horizontal force. Their effectiveness is dependent upon the sliding resistance occurring on the surface of impact, i.e., friction on rough facades (building stones, shingles) or openings in the facade, window jambs, roof eaves, etc. For the case in Blons the ratio was $P_v/P_h \sim 0.2$, in Dalaas for the least favorable case ~ 0.5 . In the event at Vals the pressure had acted downward. Pressure effects directed downward were also detected frequently in Switzerland at the foot of steep slopes (Andermatt, Zuoz).

3. Surfaces which are overrun by avalanches, are stressed by the weight of snow according to the avalanche or dammed up depth occurring under the existing circumstances.

4. From debris, stones, trees, etc., carried along, ram effects can occur, which in the case of a new installation could be allowed for by design or utilization of materials with a high degree of toughness.

5. The destructive action of the air blast, which precedes the avalanche, was small in the situations investigated and only sufficient to break windows and light doors, for which, empirically, a pressure of 500 kg/m² is enough. On the other hand the turbulence of a powder avalanche front could take effect similar to the pressure and suction effect accompanying a compression shock in air. Damages, which might have been attributed to a typical suction action, could be identified neither in the damages of the Vorarlberg nor from the available data in Switzerland.

6. The foregoing statements result from the direct observation of the destructive effects of avalanches. The next section will show to what extent they are verified theoretically.

III. ON THE DYNAMICS OF AVALANCHES.

The following explanations are collected as an approximate survey of the area to be investigated, yet they are in good agreement with the present observations. It is necessary, but not sufficient, for the formation of avalanches that a part of the sliding layer, as a result of gradient changes, damming effects, or sliding surfaces running diagonally to the movement, be pushed over the stable snow layer and, with or without the underlying snow, attain a considerable velocity. Frequently avalanches are caused by cornices, snow drifts, and snow accumulations, for example at the foot of steep slopes or bands of rock.

An essential fundamental for each avalanche investigation is knowledge of the following quantities:

γ_0 : average density of the naturally deposited snow in the sliding layer, see Table 2 for numerical values.

γ : average density of the flowing snow

h : vertically measured, total depth of the naturally deposited snow, or the depth of the sliding layer

ψ_0 : gradient in the release zone of the avalanche

ψ_u : gradient in the effects zone

If possible: A longitudinal profile of the avalanche path.

TABLE 2

Density of Snow

Loose new snow	30 to 100 kg/m ³
Felted or wind packed new snow	50 " 300 "
Dry, granular, settled old snow	200 " 450 "
Wet, settled old snow	400 " 600 "
Firn snow	500 " 800 "

1. The Phenomenon of Flow of Snow

The first movement or the breaking away of the snow is induced by a slow creeping or by the tensions caused thereby. The laminar flow exists, according to its definition, as long as the upper surface layer of the snow remains intact. This can be the case up to significant distances in slides of wet snow in which the intact snow layer is compressed into waves (Schneetuch, blanket of snow). However in other instances the laminar flow is confined to the initial stage of avalanche formation (Figures 31 and 32).

The viscosity of the water film on the snow crystals is the controlling factor for the viscosity of wet snow; the viscosity of air for the viscosity of well-aerated snow. For this the criteria of Reynolds for the beginning of turbulence yield velocities of the magnitude of 1 m/sec. In dense, dry snow larger viscosities will be in effect; it must include in all cases the disintegration of the snow blocks and then the turbulent movement if the shear resistance (for example $\tau_s \sim 50 \text{ kg/m}^2$) in vertical sections is overcome. In turbulent flow with the average velocity, v , the flow resistance per square meter of ground surface can be equated empirically as

$$\tau_s \sim \frac{\gamma v^2}{\xi}$$

in which, by analogy to hydraulics, the velocity coefficient ξ for a rough stream course can be set at $\xi \sim 500 \text{ m/sec}^2$ as demonstrated below. For $\gamma = 250 \text{ kg/m}^3$ it follows that

$$v^2 = \frac{\xi \tau_s}{\gamma} = \frac{500 \cdot 50}{250} = 100 \text{ m}^2/\text{sec}^2$$

that is, the disintegration of the snow and its turbulent movement must in all cases begin after exceeding a flow velocity of about 10 m/sec. Up to the critical velocity the snow either flows in laminar fashion or moves as a quasi-solid with frictional resistance.

The eddies of turbulent movement result in varying vertical accelerations, which, similar to the vibration of concrete, decrease the effect of the internal friction and the viscosity, so that for further flow the principles of hydraulics are largely valid.

The flow is shooting or streaming accordingly as the average flow velocity is larger or smaller than the velocity of propagation of the surface waves. A surge of incremental height Δh propagates with the velocity, w , on the flowing snow layer of height, h , and the material behind the wavefront flows after with the mean velocity, $w - v$; thus the continuity equation for the section before and after the wave front is:

$$h \cdot w = (h + \Delta h)v$$

The momentum equation for this section is:

$$(\gamma/g) h w(w - v) = \gamma/2 [(h + \Delta h)^2 - h^2]$$

From these two equations it follows that

$$(1) \quad w = [g h (1 + \Delta h/h) (1 + (1/2) (\Delta h/h))]^{1/2}$$

The wave velocity, w , increases with h and Δh , higher waves move faster than lower ones, avalanches are not flattened out during their movement, but maintain relatively abrupt boundaries (Figures 19 and 20). Figure 22 shows how sharply an avalanche tore out a gap from the middle of the village of Vals; a part of a house in the foreground was torn off by a sharp cut,

while the house standing directly behind, somewhat set back and not extending into the avalanche path, remained completely unscathed.

For small values of Δh Equation (1') applies:

(1') $w \sim [g h]^{1/2}$
 for example for $h = 2m$, and $g \approx 10 \text{ m/sec}^2$, $w \sim 4.5 \text{ m/sec}$, i.e., as a rule the flow of avalanches is shooting.

The velocity of fanning out across the direction of flow of the avalanche is likewise determined, if the terrain is plane in this direction, by the momentum principle: If Δh is the flow height of an avalanche (Bodenlawine)* over the natural snow layer of height, h , equation (1) likewise applies to the transverse propagation velocity. However, if it is a surface avalanche (Oberlawine) of flow height, h' , on the natural snow layer, then the mass overflowing across the side boundary per unit of time is $\gamma/g \cdot h' w$ and the equation of motion shows that

$$\frac{\gamma h'^2}{2} = \frac{\gamma h'}{g} w \cdot w$$

from which

(2) $w = [(g h') / 2]^{1/2}$

The material moved transversely is replaced from the mass of snow flowing in the longitudinal direction.

In terrain plane perpendicular to the direction of flow, the velocity of avalanches can be deduced from their shape of spreading with a knowledge of the flow height. For instance, this would be possible by photogrammetric interpretation of Figure 21. Here the widening of the avalanches is significant at first, diminishes with increasing velocity, and increases again toward the deposition cone. As soon as the flow of velocity of avalanches subsides to a magnitude similar to the velocity of lateral spreading, even relatively unimportant irregularities in the terrain can cause a division of the avalanche cone into different tongues (Figure 18).

When the replacement of material in the longitudinal direction is no longer sufficient to maintain the velocity of lateral expansions (Equations 1 and 2), a flattening occurs on the edges which causes a further reduction in the velocity there; this phenomenon of dying out produces the familiar tongue-shaped snow deposits of avalanches.

* Translator's Note: Bodenlawine - an avalanche to a resistant underlying layer, motion primarily on the ground.



Fig. 16. Snow slab avalanche forms a ground avalanche flowing to the right (Bodenlawine). Gandergrat (Parsenn).



Fig. 17. Ground avalanche (Grundlawine) deposition at Lavorgo 1951. Height of damming is 25 m above the tracks. Photo Military flight service.

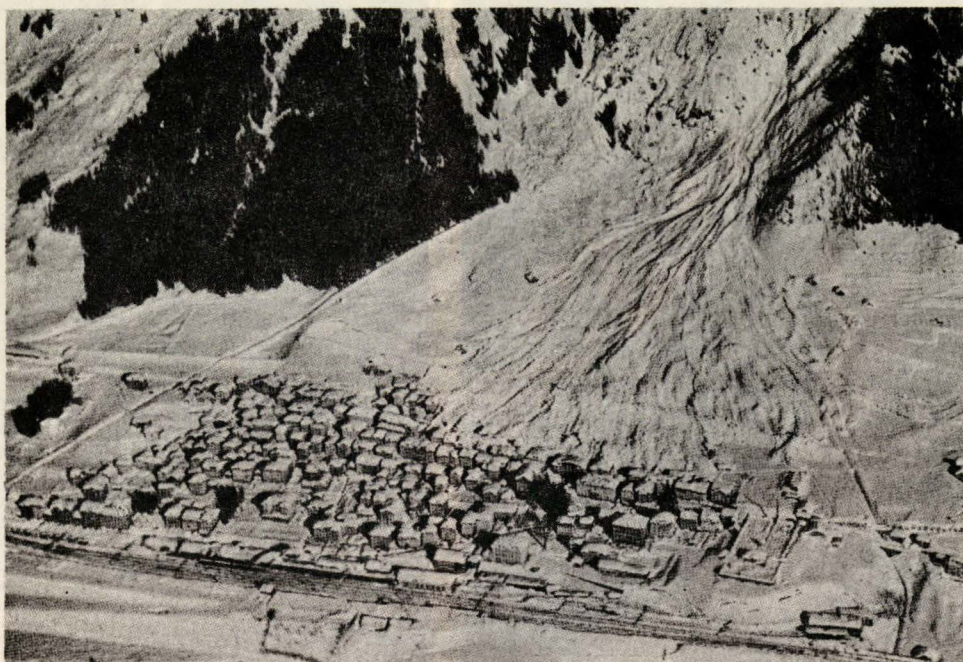


Fig. 18. Divided ground avalanche cone at Airolo 1951. Width about 400 m, length about 500 m, height about 23 m. Photo Military flight service.



Fig. 19. Powder avalanche in the Karakoram.

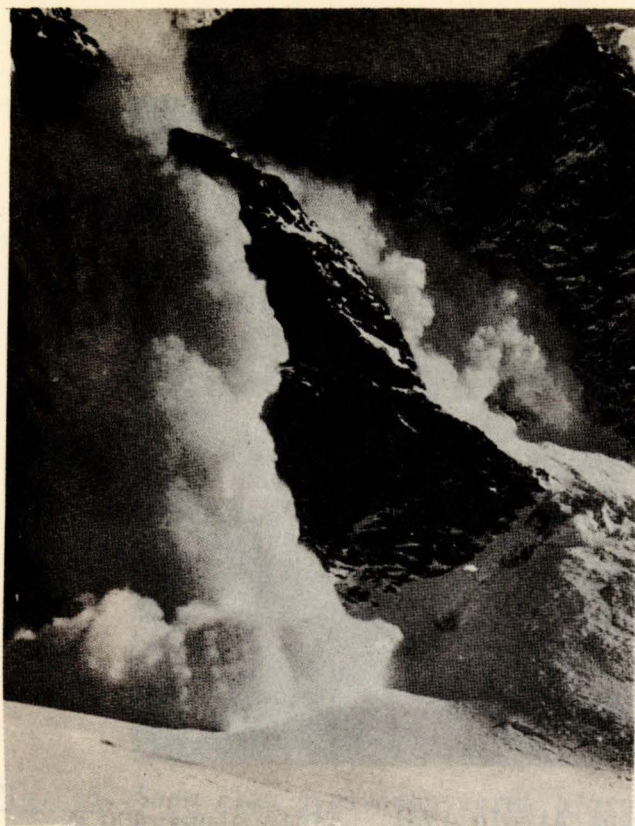


Fig. 20. Powder avalanche at Trugberg
(Jungfrau region)



Fig. 21. Spring avalanche in loose,
damp snow. Calvinen (Parsenn
region)

2. The Velocity and Flow Height of Avalanches.

A snow layer of vertically measured thickness, h' , which slides on a slope of constant gradient, ψ , sets up a frictional resistance on the base, which is proportional to the sliding area (slip coefficient ξ) and, in turbulent flow, to the second power of the velocity, v , and to the density, γ . In addition, a frictional resistance acts, which is proportional to the sliding area and to the normal pressure acting on it. Little is yet known about the friction coefficient $\mu = \tan \rho$. The angle of repose is usually 30° to 40° ; the greatest number of avalanches occur in this range of slope inclination. According to A. Roch [9] destructive avalanches are seldom released on steeper slopes, since the snow trickles down successively in small amounts. On the other hand new snow and wind packing can lead to significantly greater angles of repose. A. Roch reports that for new snow the angle of movement is 17° for initial small velocities.

This value lies at the upper limit, since avalanches frequently do not come to rest by themselves on very long slopes of about 10° gradient (Dalaas $\sim 13^\circ$). Moreover, μ increases with the density. The equation

$$\mu = \gamma / 2000 \quad (\gamma \text{ in kg/m}^3)$$

is in approximate accord with the existing observations of avalanche movement.

We are dealing with a secondary effect in the consideration of this internal friction or viscosity, which can be neglected for wet snow or powder snow avalanches. Taking into account the buoyancy of air of density

$\gamma_L = 1.25 \text{ kg/m}^3$, for a portion of the sliding snow layer of which the horizontal projection is equal to the unit of surface, the equation of motion is:

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

$$(\gamma - \gamma_L) h' \sin \psi - (\gamma - \gamma_L) h' \cos \psi \mu - \gamma/\xi v^2 = \gamma h'/g dv/dt$$

or

$$dv/dt = (g/\gamma h') [h' (\gamma - \gamma_L) (\sin \psi - \mu \cos \psi) - (\gamma/\xi) v^2]$$

The solution of this differential equation, with $k = \xi h'/g$ and $\tanh =$ hyperbolic tangent, is

$$(3) \quad v = v_{\max} \tanh [(v_{\max}/k) (t)]$$

in which the maximum velocity is:

$$(4) \quad v_{\max} = [\xi h' (1 - \gamma_L / \gamma) (\sin \psi - \mu \cos \psi)]^{1/2}$$

In most cases γ_L , γ and μ can be neglected; one can then write:

$$(4') \quad v_{\max}^2 \cong \xi h' \sin \psi$$

If the snow layer at the beginning of the distance traversed ($s = 0$) already has an initial velocity v_0 , then the proper time, t_0 , is determined from Equation (3) and for the study of the subsequent process the time $t_0 + t$ is inserted in the place of t .

The distance traversed, s , is obtained from the integration of Equation (3):

$$(5) \quad s = k \ln \cosh [(v_{\max}/k) (t)] \quad \text{where } \cosh = \frac{\text{hyperbolic}}{\text{cosine}}$$

For the initial interval t^* to reach 80% of the maximum velocity, $v_{\max}$, it is true that

$$\tanh(t^* v_{\max}/k) = 0.8$$

and by the substitution of the value t^* determined in this way into Equation (5):

$$(6) \quad s^* \cong 0.5 k$$

That is, for $\xi = 500 \text{ m/sec}^2$, one obtains $s^* = 25 h'$.

Certainly after very short initial distances the maximum velocity is nearly reached. Defense structures are destroyed, as will be shown from a study of the thrust effects, sooner from sliding snow than from its creep pressure.

If in Equation (4) the very small values γ_L/γ and μ are neglected and $\sin\psi \sim \tan\psi$ is set equal to the gradient, J , Equation (4), with $[\xi]^{1/2} = c$ and $h' = F/U$ (the hydraulic radius R of wide rectangular channels), leads to the well-known formula of Chezy:

$$v = c [RJ]^{1/2}$$

The flow velocity, v , is larger or smaller than the speed of propagation of surface waves, according to Equation (1), accordingly as J is larger or smaller than $g/\xi + \mu$. It is approximately true that for:

$$\begin{array}{lll} J > g/\xi + \mu & : & \text{shooting} \\ J < g/\xi + \mu & : & \text{streaming} \end{array}$$

that is, for $\xi \sim 500$ shooting flow certainly can occur on small gradients ($> 2\%$).

Since snow set in motion behaves very similar to a liquid it is to be expected that the coefficient $\xi = c^2$ also corresponds approximately with the determinations of hydraulics, according to which the roughness value, c , for surfaces as rough as natural ones varies between 20 and 25 and correspondingly the velocity coefficient ξ between 400 and 600. In the flow of avalanches thru forest the value of ξ can fall below the lower boundary value, on the other hand, in ground avalanches which run in a gully smoothed out with snow by preceding avalanches significantly higher values of ξ can occur. The assumption $\xi = 500 \text{ m/sec}^2$ shows a satisfactory agreement with the existing observations, which refer mostly to grassy slopes.



Fig. 22. House in Vals-Platz, of which one half was cut off sharply by an avalanche in 1951.

The integral of the motion equation neglecting the sliding resistance is:

$$v = [2 s g (1 - \gamma_L/\gamma) \sin\psi]^{1/2}$$

Since the velocity of frictionless motion never can be exceeded, ξ cannot exceed the following upper boundary value:

$$(7) \quad \xi < (2 g s) / h'$$

This boundary value is certainly almost reached after the starting distance of Equation (6). The above restriction is only necessary for Equation (4), the complete Equation, (3) does not result in exceeding the speed of free fall.

As a rule the entire motion process need not be studied in view of the short starting distance of avalanches; the further analysis can be based upon Equation (4) with $v_{\max} \cong v$.

At gradient changes from the upper slope ψ_0 to the lower slope ψ_u it is approximately true from Equation (4') and the equation of continuity that:

$$(8) \quad v_0/v_u = (h'_u \cos \psi_u / h'_0 \cos \psi_0) = \\ [(\tan \psi_u / \tan \psi_0)]^{1/3} \sim h'_u / h'_0 \sim [(\sin \psi_0 / \sin \psi_u)]^{1/3}$$

Since this equation is true for each succeeding gradient change, Equation (8) can be applied for the determination of the basic flow height h'_u at the foot of the slope. In doing so one sets

ψ_0 = gradient in the release zone

ψ_u = gradient in the zone of destruction

For small gradients ψ_u at the foot of the slope h'_u can increase at most to the dammed up height $v_u^2/2g$.

At a gradient change the transition distance to reach normal flow is even shorter than the starting distance of Equation (6), since the introduction of the continuity equation into the differential equation of motion results in raising v to a higher power in the resistance term. The complicated form of this solution is abandoned here and only a rough calculation of the run out distance of avalanches onto valley floors is given in section 3C on damming effects.

A. Surface Avalanches (Oberlawinen)*

The height of the sliding layer remains constant for a fairly long time; Equation (4), in which γ_L/γ can be neglected, serves to compute the maximum velocity. After exceeding a velocity of about 10 m/sec the blocks are disintegrated to snow powder, which, as a result of the turbulent motion of flow and the dry conditions, is gradually whirled up. On slope inclinations

* Translator's Note: Oberlawine - an avalanche of the uppermost layer of snow.

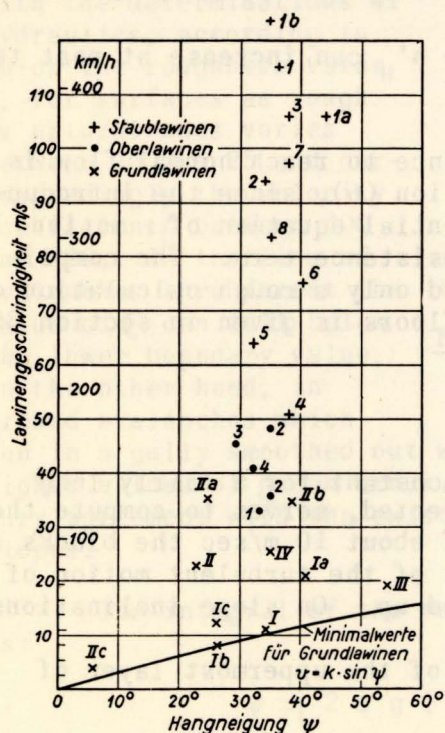
over 30° , i. e., after reaching a velocity of about 20 m/sec, the surface avalanche can, in dry cold weather, finally, partially or completely, take the form of a powder avalanche and in this way reach significantly higher velocities.

Mixed forms of surface and powder avalanches are frequent, their effects are evaluated by investigation of the borderline cases.

B. Powder Avalanches

Avalanches, which have originated through the sliding of loose snow, promote the whirling up of snow and, with appropriate conditions of the same, the formation of powder avalanches, especially in dry cold weather. Also the naturally deposited snow layer can be completely or partially carried along in the turbulent flow by the avalanche traveling over it. Whirling up of loose snow occurs as soon as the vertical component of the turbulent velocity fluctuation becomes greater than the velocity of fall of the snow particle, which increases with particle size.

From materials handling technology it is known that solid particles can be entrained in a horizontal air stream if its velocity is greater than about twice the free-fall velocity of the particles. Since the velocity of fall of snow particles reaches only 1 or 2 m/sec, the whirling up of dry fine powder snow must certainly begin after a very short running time of the avalanche, while recrystallized depth hoar requires a longer running time for this. The greater the flow velocity the sooner the formation of the turbulent layer and the mixing by air flow results.



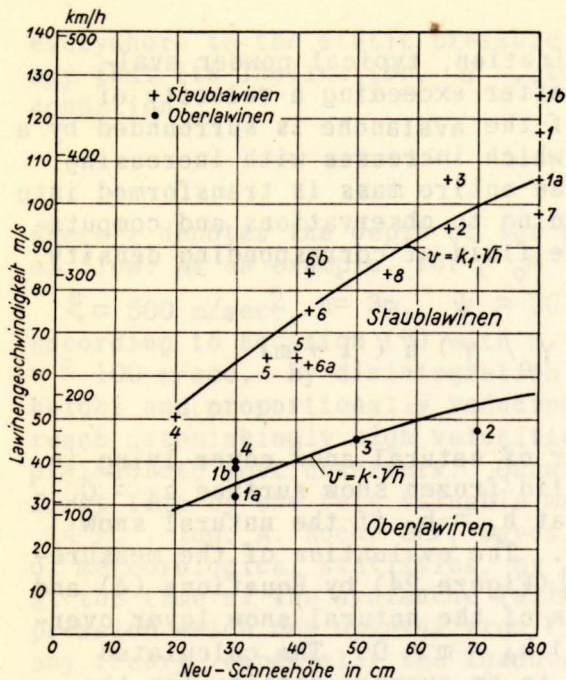


Fig. 24. Velocity of powder avalanches and surface avalanches in relation to the natural snow depth - (Evaluation by Engineer A. Roch, Davos, of the values measured by Dr. M. Oechslin.)

Ordinate - avalanche velocity m/sec
Abcissa - new snow depth in cm
Staublawinen - powder avalanches
Oberlawinen - surface avalanches

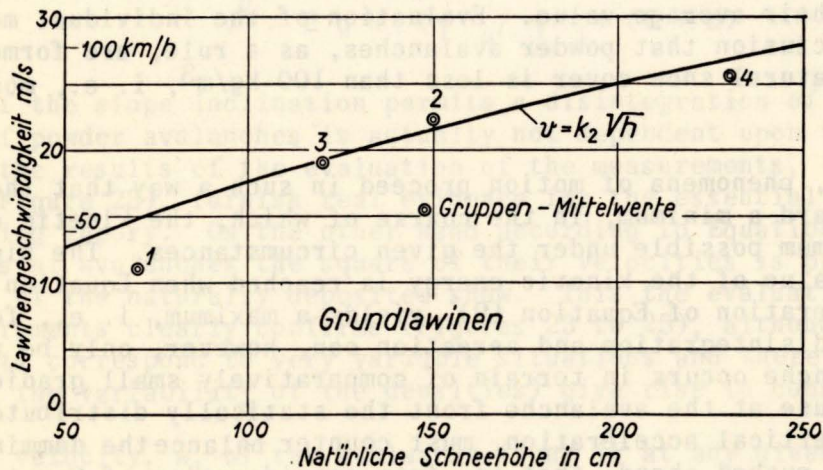


Fig. 25. Velocity of ground avalanches (Grundlawinen) as a function of natural snow depth. (Values measured by Dr. M. Oechslin evaluated by Engineer A. Roch, Davos.)

Ordinate - Avalanche velocity m/sec
Abcissa - Natural snow depth in cm
Gruppen - mittelwerte - mean value of the group

On slopes of more than about 30° inclination, typical powder avalanches can form from as yet unloosened snow after exceeding a velocity of 15 to 20 m/sec. To begin with the nucleus of the avalanche is surrounded by a turbulent layer of air with suspended snow, which increases with increasing velocity and running time, so that finally the entire mass is transformed into a more or less uniform aerosol, which, according to observations and computations, behaves very similar to a compressible fluid of corresponding density. The velocity conforms to Equation (4) with

$$(9) \quad h' = (\gamma_o / \gamma) (h + h_A) = (\gamma_o / \gamma) h (1 + m)$$

where $h \geq h_A \geq 0$, $m = h_A/h$

h_A is the height of the whirled up layer of natural snow cover lying in front of and under the avalanche. With a solid frozen snow surface $h_A = 0$, while in exceptional cases it can be true that $h_A = h$, if the natural snow cover consists of dry powder snow throughout. The evaluation of the measurements of Canton Forester Dr. M. Oechsli [4] (Figure 24) by Equations (4) and (9) shows that, as a rule, the disintegration of the natural snow layer overrun may be neglected and thus in Equation (9) $h_A = m = 0$. The calculated average curve shown in Figure 24 corresponds to an average density for the natural snow cover of 75 kg/m^3 . The deviations of the individual values from the calculated average curve are caused by the deviations of the effective densities from their average value. Evaluation of the individual measurements leads to the conclusion that powder avalanches, as a rule, are formed when the density of the natural snow cover is less than 100 kg/m^3 , i. e., mostly in fresh new snow.

In nature, phenomena of motion proceed in such a way that the potential energy tends toward a minimum, in the course of which, the kinetic energy reaches the maximum possible under the given circumstances. The highest possible boundary value of the kinetic energy is reached when Equation (4), including consideration of Equation (9), yields a maximum, i. e., for $\gamma = 2 \gamma_L$. This optimum of disintegration and aereation can, however, only be reached, if the powder avalanche occurs in terrain of comparatively small gradient (Figure B), because at the avalanche front the statically distributed force, neglecting the vertical acceleration, must counterbalance the damming force of the air which is pushed ahead, that is, from consideration of Equation (4) and neglecting μ

$$(\gamma - \gamma_L) h_o \gamma_o / \gamma = \gamma_L v^2 / 2g =$$

$$(\gamma_L / 2g) \xi h_o (\gamma_o / \gamma) (1 - \gamma_L / \gamma) \sin \psi$$

from which

$$(10) \quad \gamma = (\gamma_L / 2g) \xi \sin \psi$$

Moreover the damming pressure of the air $p_s = \gamma_L v^2 / 2g$ remains equal

everywhere to the static pressure at the wave front, if this curves in such a way that its inclination, α , to the flow direction everywhere fulfills the condition

$$\sin \alpha = z/h$$

where z denotes the depth of the point observed below the undisturbed surface of flow. As an example, for $\gamma_o = 100 \text{ kg/m}^3$, $\gamma_L = 1.25 \text{ kg/m}^3$, $g = 10 \text{ m/sec}^2$, $\xi = 500 \text{ m/sec}^2$, $h = 3\text{m}$, $\psi = 30^\circ$, according to Equation (10): $\gamma = 15.6 \text{ kg/m}^3$; according to Equation (9) with $m = 1$: $h_{\max} = 39 \text{ m}$, and from Equation (4'): $v \approx 100 \text{ m/sec}$. By disintegration and aëration, that is by increasing the height and proportionally reducing the flow resistance, powder avalanches reach astonishingly high velocities, whose origin until now remained unexplainable to most observers. Quantitative data were given for this for the first time by the very valuable measurements of Canton Forester Dr. M. Oechslin [4]. Ing. A. Roch, SLF, Davos, made possible their evaluation, on the basis of meteorological statistics, by later determining the snow heights existing at the time of the avalanche falls described by Dr. Oechslin. The first impression which one obtains from Figure 23 had almost lead to the rejection of any theory, especially the fundamental Equation (4). However, when the value for γ from Equation (10) is introduced into Equation (4'), the following astonishing consequence results:

$$(11) \quad v^2 = 2 g h (\gamma_o / \gamma_L) (1 + m)$$

that is, if the slope inclination permits a disintegration of the snow, the velocity of powder avalanches is actually not dependent upon the slope inclination and the results of the evaluation of the measurements, incomprehensible at first (Figure 23), furnish real evidence for the essential correctness of the preceding theory. On the other hand according to Equation (4') for all other kinds of avalanches the square of their velocities is proportional to the height of the naturally deposited snow. This the evaluation of the available measurements clearly confirms (Figures 23 to 25), although these measurements correspond to very variable situations and therefore (especially because of the variability of the densities) give rise to considerable scatter.

The velocity, w , of the avalanche front is at any given time somewhat smaller than the flow of velocity, v , of its central part given by Equation (11), since the damming pressure at the avalanche front causes back eddying of the snow similar to that which the airstream shows during the intrusion of cold air into a valley. At a reference plane moving with the avalanche front the air strikes with a velocity, w , while behind it the snow flows with the velocity $v - w$. The continuity of the pressure distribution through the avalanche front is maintained according to

$$(\gamma/2g) (v - w)^2 = (\gamma_L/2g) w^2$$

from which

$$(12) \quad w = v / (1 + [\gamma_L / \gamma]^{1/2})$$

The refinement which would result thereby in the solution of Equation (10) turns out to be negligibly small. When the avalanche front strikes the quiet air this is compressed, up to the damming pressure $p_s = \gamma_L \cdot w^2/2g$. This pressure increase produces compression waves, which precede the avalanche approximately with the velocity of sound, a . From the relationships of gas dynamics [10] for compression shock it follows for air blasts of small intensity that:

$$(13) \quad \Delta p = (\gamma_L/g) a w$$

In this equation

$$\begin{aligned} a &\cong 340 \text{ m/sec: the velocity of sound in air} \\ w &= \text{the velocity of the air flowing behind the blast} \\ \gamma_L &\cong 1.25 \text{ kg/m}^3 : \text{the density of air} \end{aligned}$$

If the reference plane is moved with the avalanche front, then the air flows toward this reference plane with the velocity of the avalanche front. If the velocity of material, w , in Equation (13) becomes equal to the velocity of the avalanche front, a frontal wave must form whose pressure increase is given by this equation. The frontal wave cannot be broken up into smaller pressure waves of finite size, since their material velocity would be smaller than the flow velocity, w ; such waves are repulsed in the frontal wave. On the other hand waves with very small material velocity and pressure increase radiate continuously from the frontal wave with the velocity of sound. Similar phenomena are observed in the bow waves in front of ships or damming waves in front of bridge piers. The elemental pressure waves of intensity p_s emanating from the damming point of the avalanche front with the velocity of sound, a , accumulate in the frontal wave an average of t seconds with the result that the higher pressure Δp is maintained there, that is:

$$p_s \cdot a \cdot t \cong \Delta p$$

During this time the avalanche front has advanced approximately $t \cdot w$. The distance by which the air blast precedes the avalanche is then

$$(14) \quad l = (a - w) t = (a - w) \Delta p / a p_s$$

For examples for $w = 100 \text{ m/sec}$ and $\gamma_L = 1.25 \text{ kg/m}^3$, $p_s = 625 \text{ kg/m}^2$, $\Delta p = 4250 \text{ kg/m}^2$, and $l \cong 5 \text{ m}$
for $w = 50 \text{ m/sec}$ then $p_s = 156 \text{ kg/m}^2$, $\Delta p = 2125 \text{ kg/m}^2$ and $l \cong 12 \text{ m}$.

The air blast precedes the avalanche farther the smaller the velocity of the avalanche, however at the same time the intensity of the blast decreases proportionally with the velocity.

Experimental data for the verification of this simple attempt at calculation of complicated phenomena are lacking at the present time. On the other hand the effect of the air blast preceding the avalanche certainly has

been observed frequently, for example this has caused light structures to be pushed over ahead of the avalanche front. In many cases the effect of a very lightly loaded powder avalanche of great velocity preceding the main part of the avalanche is erroneously designated as air blast.

For instance the opinion has been expressed that the victims of the 1951 Gastein avalanche were killed by the air blast, because the lung lesions typical of it were established by medical findings. The investigation of explosion catastrophies carried out earlier by the author has shown, however, that these phenomena first appear as a result of air blasts of about three atmospheres over pressure, which, as pointed out above, are never reached from the air blast of an avalanche. On the other hand this over pressure is in agreement with the highest damming pressure of powder avalanches. As a result of damming, the air escaping from the snow-air mixture and penetrating all openings reaches the same pressure as the damming pressure of the avalanche itself.

The observation on suction effects of powder avalanches are mostly explainable by eddy effects. Probably the avalanche entrains air; however, from investigations of the turbulent mixing process it is concluded that the velocity of the air streaming in from the side can hardly reach 1/20 of the avalanche velocity. Significant suction formed behind the avalanche would automatically cause an aerodynamic match of the shape of the avalanche tail and the suction would in this way be further reduced. "The material is tricky" reads a motto handed down from Prof. W. Ritter.

On the other hand suction effects are possible behind small obstacles completely overrun by powder avalanches of great velocity, which can reach at most

$$(13a) \quad p(-) = (\gamma_L/2g)w^2 \cong w^2/16$$

Also portals of tunnels or galleries, or other openings in structures, can be overrun by a powder avalanche in such a way that they act similar to an injector [11].

As a result of successive disintegration and aeration of the snow, and the resulting increase in height and decrease in the relative resistance to flow, powder avalanches reach astonishingly high velocities (up to about 100 m/sec). Their effect generally reaches the entire height of structures. If the powder avalanche occurs in a gully or ravine and is deflected, the upper part of the powder avalanche can flow further in the original direction. Powder avalanches frequently divide (Figure 20). As a result of the large velocity powder avalanches or parts of them frequently leave the ground at breaks in the terrain and can shoot through the air in a free jet.

Equation (10) shows in combination with Equation (9) that when a powder avalanche strikes level terrain ($\psi \rightarrow 0$), γ can become very small and h' very large. The powder avalanche loses specific mass and velocity after dissipation of its kinetic energy, disintegrates gradually to clouds of snow, and finally the snow settles again. Until this occurs, however, powder avalanches

can still cause damage over large distances even on opposing slopes; not infrequently debris, trees, stones, and the like are observed thrown far uphill on the opposing slope (for example avalanches at Gastein, St. Antonien, and Monstein, all in 1951).

C. Avalanches to a Resistant Underlying Layer (Bodenlawinen)

When the snow is so compacted that no significant dust cloud occurs during movement, or in damp and wet snow, whose particles are held together by the surface tension of the water film between them, a densification of the snow occurs caused by the damming pressure of movement instead of a reduction in the average density due to disintegration and suspension accompanying movement. The sliding snow layer, on the average becoming heavier, during turbulent descent works itself into the underlying natural snow layer until finally a ground avalanche (Grundlawine) is produced, which passes through the snow cover right to the ground like a snow plow and not infrequently carries along scree, trees and surface layers of earth, especially if the latter are soaked by thawing weather. The darker color of the ground avalanche (Grundlawine) frequently observed (Figure 17) arises from the mixing of the snow with scree, sod and pieces of soil.

Ahead of the avalanche front the existing snow cover surges upward from a compression shock. If h' designates the front height of the avalanche, the average density of the natural snow cover surging upward immediately ahead is $\gamma_v = \gamma_0 h / h'$. In the compression wave preceding the avalanche the static pressure of the natural snow cover climbs to the damming pressure, this causes a rolling back of the avalanche front, whose velocity is reduced to the value given by Equation (12) if the value γ_v is inserted in this equation in place of γ_L .

On the other hand the continuity of mass flow must be taken into consideration: if a longitudinal strip from the avalanche one meter wide is considered, then the mass $\gamma_0 h v$ flows from the natural snow cover in one second up to a moving reference plane whose velocity is v , that of the avalanche snow, while the mass $\gamma h' v'$ flows away from the reference plane. The average decrease in velocity behind the avalanche front is therefore:

$$v' = (\gamma_0 h / \gamma h') v$$

and thus the effective thrust velocity of the avalanche front is:

$$(15) \quad w = v - v' = v[1 - \gamma_0 h / \gamma h']$$

The energy equation (12) (with $\gamma_L = \gamma_v$) and the continuity equation (15) are satisfied simultaneously by natural adjustment of the flow height h' :

$$w = v / (1 + (\gamma_0 h / \gamma h')^{1/2}) = v(1 - \gamma_0 h / \gamma h')$$

from which it follows that:

$$(\gamma_0 h / \gamma h')^{1/2} = 1/2 (5)^{1/2} - 1)$$

$$(16) \quad \gamma h' = 2.6 \gamma_0 h$$

During the descent the damming pressure in the avalanche front reaches the value:

$$p_s = \gamma_v v^2 / 2g = (\gamma_0 h / 2gh') v^2 (1 - \gamma_0 h / \gamma h')^2 = 0.146 \gamma v^2 / 2g$$

or, taking into consideration Equations (4') and (16):

$$p_s = (0.38/2g) (\gamma_0 h \xi \sin \psi) \approx 0.02 \gamma_0 h \xi \sin \psi$$

It can be shown that the influence of the compressibility of snow (compare the next section) on the flow height h' of the ground avalanche (Grundlawine) is small, so that for the flow phenomenon one can set

$$(16') \quad h' \approx 2.6 h$$

The maximal velocity is calculated by Equation (4), in which, for wet snow, μ is approximately zero.

The fundamental correctness of the theory is proved by evaluation of the measurements compiled in Figures 24 and 25; the square of the velocity proves to be proportional to $\sin \psi$ and h . The use of Equation (4) with the average value of the measurements shows for the observed ground avalanches (Grundlawinen)

$$\xi = 500; \quad \mu = 0.075$$

and assuming the relation $\mu = \gamma_0 / 2000$ it would be true that $\gamma_0 = 150 \text{ kg/m}^3$, possibly however, larger snow densities correspond to a smaller average value of μ as a result of the influence of moisture content.

Ground avalanches (Grundlawinen), because of their relatively small velocity, follow existing gullies or terrain depressions faithfully; the flow phenomenon is completely equivalent to that of torrents (see the next section).

In the zone where the snow is deposited, significant damming cones frequently are formed (see the next section under C and Figure 28).

3. Damming and Pressure Effects

A. Energy Equation

The basis for the calculations is the equation of motion for compressible fluids of Euler-Bernoulli, in which the frictional resistance of the usually short damming distance is neglected:

$$(17) \quad z' + v^2 / 2g + \int_{p_0}^{p_0+p} dp / \gamma = H$$

In this equation z' is the height of the points being considered measured from a horizontal reference plane and in one and the same flow line. In addition:

$$\begin{aligned} v &= \text{the velocity at the point under consideration} \\ \int_{p_0}^{p_0+p} dp / \gamma &= \text{the pressure head, which is dependent upon the compressibility, above the reference pressure head, } p_0 \\ p = \gamma Z &= \text{the specific pressure at the point being considered, and at the depth } z \text{ below the surface of the avalanche being subjected to the damming effect.} \\ H &= \text{the energy head, i. e., the energy per unit weight of fluid at the point under consideration.} \end{aligned}$$

With the postulate that during an avalanche the quantity of flow per unit time must remain approximately constant, Equations (4) and (17) show that the uniform contractions of the cross section of the gullies and ravines through which avalanches run cause increases in velocity as a rule, while during expansions the velocity is reduced in proportion to the velocity of lateral spreading.

B. Compressibility of Snow

a) The dynamic, elastic compression of snow is limited chiefly by the compressibility of the air in the voids; the framework of ice crystals gives only slight resistance to compression, while the compressibility of the ice itself is negligible compared to that of the material in the pores. Accordingly the compressibility of snow saturated with water also can be neglected here. Air in the pores is not completely expelled from the snow by high pressure. For dry snow the maximum density γ_F obtained by rapid compression will correspond approximately to that of firmly consolidated firn snow ($\gamma_F \sim 800 \text{ kg/m}^3$), for coarse grained dry snow the upper boundary value can decrease to $\gamma_F \sim 600 \text{ kg/m}^3$, while for wet snow the upper boundary value of the liquid ($\gamma_F \sim 1000 \text{ kg/m}^3$) can almost be reached.

The density of snow can be written:

$$(18) \quad \gamma = \gamma_F (1 - V_L) + V_L \cdot \gamma_L$$

where V_L denotes the volume of air which is expellable per unit volume; it can be expressed from the foregoing equation as:

$$(18') \quad V_L = (\gamma_F - \gamma) / (\gamma_F - \gamma_L) \sim 1 - \gamma / \gamma_F$$

under atmospheric pressure, $p_0 = 1 \text{ atmosphere} \sim 10,000 \text{ kg/m}^2$, γ is set equal to

γ_0 in the preceding equation. The compression of the air in the pores of the snow can be considered to be isothermal since the heat developed is immediately absorbed by the snow. According to Boyle-Mariotte:

$$(18'') \quad (p_0 + p) V_L = p_0 (\gamma_F - \gamma_0) / \gamma_F = p_0 V_{L0}$$

$$V_L = p_0 / (p_0 + p) \cdot (\gamma_F - \gamma_0) / \gamma_F$$

Under the dynamic overpressure p (greater than $p_0 = 1$ atmosphere) the density of the snow (weight/ compressed volume) is:

$$(19) \quad \gamma_d = \gamma_0 / (1 + V_L - V_{L0}) = \gamma_0 (1 + p/p_0) / (1 + \gamma_0 p / \gamma_F p_0)$$

The dynamic pressure head amounts to:

$$(20) \quad \int_{p_0}^{p_0 + p} dp / \gamma = p / \gamma_F + (p_0 / \gamma_0) \cdot (1 - \gamma_0 / \gamma_F) \ln(1 + p/p_0)$$

as an example, for $\gamma_0 = 300 \text{ kg/m}^3$, $p_0 = 10,000 \text{ kg/m}^2$
 $\gamma_F = 800 \text{ kg/m}^3$, $p = 10,000 \text{ kg/m}^2$

$$\int_{p_0}^{p_0 + p} dp / \gamma = 27.0 \text{ m} = p / \gamma_m; \text{ that is } \gamma_m = 370 \text{ kg/m}^3$$

According to Equation (19) under the dynamic pressure $p = 10,000 \text{ kg/m}^2$
 $\gamma_d = 436 \text{ kg/m}^3$. The average value during the compression amounts to:

$$(21) \quad \gamma_m = (\gamma_0 + \gamma_d) / 2 = \frac{\gamma_0 + (\gamma_0 / 2)(1 + \gamma_0 / \gamma_F)p/p_0}{(1 + \gamma_0 p / \gamma_F p_0)}$$

In the preceding case $\gamma_m = 368 \text{ kg/m}^3$; in other words the pressure calculation may be carried out using γ_m from Equation (21) as for an incompressible material.

The static compressibility of snow is dependent in a complicated way upon the magnitude and duration of the pressure as well as upon the temperature, the character of the snow, and metamorphism. A fairly correct picture of the actual behavior can be obtained by the hypothesis that the compression of the air in the pores, brought about first by the pressure, is equalized during settlement of the snow material. Then, without altering the settlement which has taken place, the air in the pores escapes.

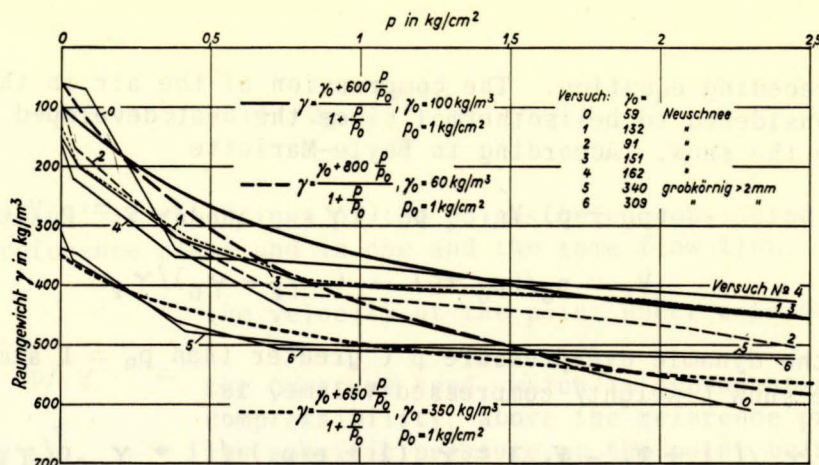


Fig. 26. Compression of snow of various densities (S.L.F.) Ordinate -Density in kg/m^3 ; Abcissa - p in kg/cm^2 ; Versuch -Experiment; Neuschnee- new snow; grobkörnig - coarse grained.

According to this hypothesis Equations (18) and (18'') give:

$$(22) \quad \gamma_{\max} = \left(\gamma_0 + \gamma_F \frac{p}{p_0} \right) / \left(1 + \frac{p}{p_0} \right)$$

For the foregoing numerical examples $\gamma_{\max} = 550 \text{ kg/m}^3$.

The generally good agreement of this equation with compression experiments is evident from Figures 26 and 27 (experimental results of S. L. F.).

The compressions shown in Figure 27 are, at relatively high temperature, larger initially and become smaller at higher pressure than those at low temperature. Rapid compression of snow can cause an initially noticeable heating of the air in the pores; the adiabatic maximum value of the absolute temperature $T = 273 + t$ attained without heat flow is:

$$T = T_0 \left(1 + \frac{p}{p_0} \right)^{(x-1)/x}$$

where T_0 is the temperature at the initial condition where $p_0 = 1$ atmosphere and p is the overpressure exceeding atmospheric pressure. The ratio of the specific heats of air for constant pressure and constant volume is:

$$x = c_p / c_v = 0.237 / 0.169 = 1.4$$

The initial heating and the subsequent cooling of the air in the pores effects an intensive metamorphism of the snow crystals, which operates more distinctly the higher the initial temperature. The average heating of the snow remains small in this process and hardly exceeds $1/20^\circ \text{C}$ at the pressure in question here.

Figure 26 shows the order of magnitude of the influence of the condition of the snow (age, original density, texture, and grain shape) upon its

compression.

The usually high density and strength of avalanche snow in its region of damming and the frequently demonstrated "freezing in" of the victims of avalanches as soon as they come to a standstill are explainable by the development of heat due to flow resistances and compression, which produces first a surface melting and a freezing together of the snow crystals after the compression. From the estimates of Section 2 it can be shown that the total frictional and compression work converted to heat per cubic meter of avalanche snow reaches approximately the value $(\gamma - \gamma_L) \cdot H$ if the avalanche comes to rest after the height of fall H measured vertically. The heat from friction and compression approaches approximately

$$W = (\gamma - \gamma_L) H / 427 \text{ kcal/m}^3$$

If the air temperature lies in the neighborhood of the freezing point, the heat from friction and compression can melt $W/80$ kilograms of ice per cubic meter of avalanche snow. Which, at any given time, will occur on the surface of the snow crystals. As soon as a film of water forms on the surface of the particle the coefficient of moving friction μ is reduced to a fraction of the coefficient of static friction, as has been confirmed frequently by investigations of various materials. If the initial temperature of the snow

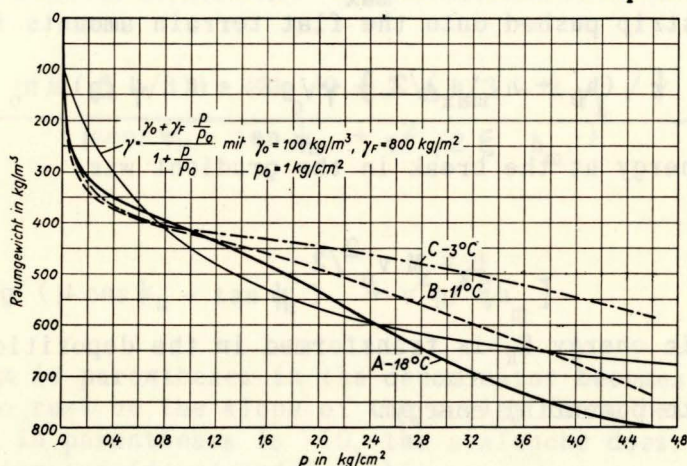


Fig. 27. Compression of snow at various temperatures. Ordinate - Density in kg/m^3 ; Abcissa - p in kg/cm^2 ; mit - with.

lies below the freezing point, its average heating by friction and compression will reach about $\Delta t = 2W/\gamma$, if the specific heat of snow is taken as $1/2 \text{ kcal/kg/}^\circ\text{C}$.

The consequences of these secondary thermal effects are not considered further here, since the investigation of a few examples has shown that this does not impair the fundamental usefulness of the laws of compression derived in this section.

Equation (22) is the basic one for the calculation of the final height of damming, while Equation (21) is to be applied in the calculation of dynamic pressure effects. For deposition of snow by sedimentation from powder avalanches smaller densities can occur than those given by Equation (22).

C. Damming Effects

With diminishing slope inclination the flow height h_u of the avalanche increases according to Equation (8). It comes to a stop when, according to Equation (17), the flow height plus the pressure level reaches the energy level.

Of great interest is the run out distance of the avalanche onto flat valley floors; all too often only the front of an avalanche has reached a few structures and swallowed up victims, which obviously would have been avoided if a small amount of the energy of the avalanche had been dissipated. If, in a broad avalanche, a longitudinal strip 1 meter wide is considered, which has a flow height h_0 and a velocity v_0 and pushes down below a slope of inclination ψ_0 onto the valley floor (with a slope ψ_u , positive or negative), then, providing the slope of the valley floor is sufficiently small, the avalanche comes to rest after a run out distance s (measured from the break in the gradient). During this time the snow increases approximately by the damming height $v^2/2g$ to a cone of maximum height $h_{\max} = h_0 + \Delta h$. Accordingly, the mass of the 1 meter wide strip pushed onto the flat terrain amounts to approximately:

$$M = s \left[(h_0 + h_{\max})/2 \right] \gamma/g = s \left(\gamma/g \right) (h_0 + \Delta h/2)$$

and its kinetic energy at the break in the gradient was:

$$E_k = M v_0^2/2$$

This kinetic energy E_k is transformed in the deposition of the snow:

a) Into potential energy:

$$E_p = Mg \eta$$

$$\text{where } \eta = \left[(3h_0 + 2 \Delta h) / (2h_0 + \Delta h) \right] \left[\Delta h/6 - (s/3) \tan \psi_u \right]$$

and signifies the elevation of the center of gravity of the wedge (of snow).

b) Into frictional work: The deposited mass M in flat terrain moves the center of gravity ζ against the frictional force $Mg \mu \cos \psi_u$ and thereby performs the work:

$$A_R = \zeta \cdot M \cdot g \cdot \mu \cdot \cos \psi_u = M \cdot g (s/3) [(3h_0 + 2 \Delta h) / (2h_0 + \Delta h)] \mu \cos \psi_u$$

c) Into flow work: Per unit area of sliding surface the flow resistance is: $\gamma v^2 / \xi$.

The velocity diminishes successively from v_0 to 0; the average of its square is approximately $v_0^2/2$. The work performed in the runout distance s is:

$$A_V = (\gamma / \xi) (v_0^2/2) s \zeta$$

d) With increasing disintegration the resistance of the individual snow particle contributes noticeably to a portion of the work A_S :

$$A_S \cong (M g / \gamma_F) (\gamma_L v^2/2g)$$

From $E_K = E_p + A_R + A_V + A_S$, with $h_m = h + \Delta h/2$ and $h_{\max} - h_0 = \Delta h \cong v^2/2g$ and neglecting the usually small reduction in the height of damming due to the frictional resistance over the relatively short damming distance, it follows that:

$$s = \frac{[v^2 / (2g(h_0 + 2 \Delta h/3)) (3h_0/2 + 2 \Delta h/3 - 2 \gamma_L / \gamma_F) h_m]}{(\mu \cos \psi_u - \tan \psi_u + v^2 / 2 \xi h_m)}$$

or

$$(23) \quad s \cong v^2 / [2g (\mu \cos \psi_u - \tan \psi_u) + v^2 g / \xi h_m]$$

If the term in parentheses in the denominator becomes ≥ 0 , the avalanche comes to rest on the slope of the valley floor being considered. If however, the term in parentheses is < 0 , the avalanche does not come to rest in the terrain being considered and for this

$$\sin \psi_u \geq (1/2\mu) [(1 + 4 \mu^2)^{1/2} - 1]$$

for small values of v

or

$$\tan \psi_u \geq v^2 g / \xi (2h_0 g + v^2) \text{ for } \mu \sim 0$$

In this case the above equation for s gives approximately the transition distance until normal flow again occurs and where $h_u = h_0 (\sin \psi_0 / \sin \psi_u)^{1/3}$

$$s_u \approx (v_o^2 - v_u^2) / 2g (\mu \cos \psi_u - \tan \psi_u)$$

For $s_u < 1$, in streaming flow a damming curve can form in the upper part of the slope ψ_o , in shooting flow a sudden change in height can occur near the region of the gradient change for which the methods of water level calculation can give more accurate information.

The momentum equation for a very wide avalanche shows that for the maximum cross section of the damming cone:

Force = Mass x Loss of velocity

$$(\gamma_{\max}/2) (H'^2 - h'^2) = \gamma' / g h' v v' \quad (\gamma' = \text{density of the flowing snow})$$

$$(24) \quad H' = h' [1 + (2 \gamma' v^2) / g h' \gamma_{\max}]^{1/2}$$

or from Section 3 a, b:

$$H' \approx (\gamma_m / \gamma_{\max}) (v^2 / 2g + h')$$

as an example, for $h' = 5\text{m}$, $v = 23\text{ m/sec}$, $p_s = \gamma_m v^2 / 2g = 10,000\text{ kg/m}^2$, (with densities according to the example accompanying Equation (20) and $\gamma' \approx \gamma_o$), it is computed that $H = 18\text{ meters}$. The avalanche cones can reach considerable heights (Figure 28).

The height of deposition is decreased in flat deposition terrain by lateral expansion; the approximate shape of the deposition cone could be calculated by using Equations (2), (3), (8), and (22) taking into consideration continuity. If the terrain is such that the maximum cross section of the deposition cone is geometrically similar to the flow cross section of the avalanche, then

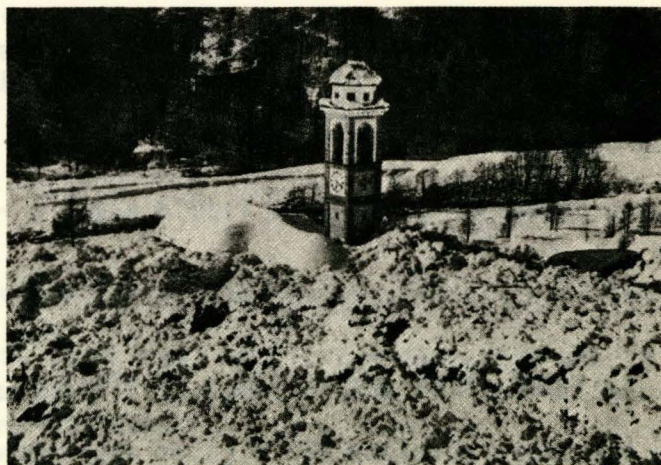


Fig. 28. Avalanche cone at Frasco, Verazascatal, 1951.

$$(24') \quad H' = h' [1 + (2 \gamma' v^2)/g \gamma_{\max} h']^{1/3}$$

The numerical illustration given above would lead to a damming height of about 12 meters.

D. Thrust Effect of Avalanches

Referring to Equations (17), (21), and (22), the specific thrust pressure near the underlying surface (Boden) may be written:

$$(25) \quad p = \gamma_m (h' + v^2/2g) = \gamma_m H = \gamma_{\max} H'$$

$$\text{where } \gamma_m = [\gamma + (\gamma/2) (1 + \gamma/\gamma_F) p/p_0] / [1 + (\gamma/\gamma_F)(p/p_0)]$$

$$\gamma_{\max} = (\gamma + \gamma_F p/p_0) / (1 + p/p_0)$$

H' = maximum damming height

From a combination of the equations it follows that:

$$(25') \quad p = \gamma_F [((q/2)^2 + H p_0 / \gamma_F)^{1/2} - q/2]$$

$$\text{in which} \quad q = p_0 / \gamma - (H/2) (1 + \gamma / \gamma_F)$$

The uppermost boundary value for p is the specific thrust pressure from the equation of momentum:

$$(25'') \quad p_{\max} = \gamma_m (h' + v^2/g)$$

This maximum pressure can occur, however, only if the snow is plastered onto the obstacle by inelastic impact and remains there without damming up or flowing laterally. However, inasmuch as snow flows like a fluid which is dammed up on impact and flows off laterally, Equation (25) is valid. Occasionally Equation (25'') also is quoted erroneously in the literature for this situation, because the momentum equation was not applied to a complete control surface, i. e., the pressure distribution was not taken into consideration beyond the cross section of the impinging stream.

Separation of snow from the aerosol can only occur in the following cases:

a) By sedimentation if the velocity of the aerosol falls below about 6/5 of the velocity of fall of the particles in air.

b) If the aerosol is so lightly loaded with solid particles, i.e., if the snow is so thoroughly disintegrated that, with a sudden drop in velocity of the air, Δv , (for example as a result of obstruction), no adjacent

particle lies within the laminar boundary film of the particle. The snow is then plastered onto the damming obstruction. The equilibrium of the shear stresses acting on the individual granule as a result of the viscosity of the air η and the density of the entrained air permits one to assume the following qualitative relationship (in technical units, $\eta \sim 1.7 \times 10^{-6} \text{ kg-sec/m}^2$):

$$\text{thickness of the boundary layer } \delta \sim (2 \eta \Delta v / \gamma_L)^{1/2}$$

for $\Delta v \sim 50 \text{ m/sec}$ the thickness of the entrained air layer reaches already about 1 cm. Separation of snow begins either at lower air velocities or by damming of air at higher velocities, if this is only lightly loaded with snow, i. e., if the density of the snow-air mixture is small.

If the distance between particles is smaller than the thickness of the boundary layer, then the aerosol at the velocity corresponding to this must behave mechanically like a homogeneous gas of corresponding average density.

The above indications show that the effect of obstructions on the movement of snow laden air currents still needs clarification.

For more accurate investigations a value of v corresponding to the velocity distribution v' is inserted in Equation (25). The investigations of Bazine and Boussinesq lead one to expect a parabolic velocity distribution for the circumstances in question, i. e., the velocity v' at the depth z below the surface is:

$$(26) \quad v' = v [4/3 - (z/h')^2]$$

This kind of velocity distribution generally is in agreement with the measurements of Bagnold [12]. As an additional limiting case, for powder avalanches with strong back damming of the front along with consideration of the relative back flowing motion at the surface, the ordinate z to be inserted in the equation above is measured above and below half the flow height.

The velocity near the underlying surface amounts to one third the average velocity v . The velocity distribution is of great influence on the pressure effect of powder avalanches, which have a great flow height h' .

For the pressure on inclined surfaces for shooting flow the following is true: if a stream of cross section f and velocity v strikes a solid surface at an angle β , then one can think of the stream as being divided into a stream of cross section $f \cos \beta$ parallel to the surface struck and a stream of cross section $f \sin \beta$ perpendicular to this surface. In the second instance the mass $m = f \gamma / g$ flows with the velocity $v \sin \beta$ against the solid surface. The uniform specific damming pressure originates from the transmission of pressure into the deflected material:

$$(27) \quad p_\beta = (f \gamma / g) (v^2 \sin^2 \beta / 2f \sin \beta) = (\gamma v^2 / 2g) \sin \beta$$

The specific resistance of an inclined surface referred to the projection in the flow direction is likewise given by Equation (27). This rule

agrees with existing observations better than with the complicated results of the flow theory.

The total resistance of a prism of square horizontal projection is not changed by rotation about its vertical axis. The total pressure on a circular cylinder of radius r is:

$$(27') \quad P = (\gamma r v^2 / 2g) \int_0^\pi \sin^2 \beta = (\pi / 2) (r \gamma v^2 / 2g)$$

If an avalanche of width B flows around an obstacle of width b , or if barriers of total width b stand in front of a structure of width B , a loss of energy is brought about by the obstacle or the barriers. According to the momentum equation per unit of time it amounts to:

$$P = (m/dt) (v_1 - v_2) = bh \gamma v^2 / 2g = Bh (\gamma / g) v \Delta v$$

The loss in velocity is $\Delta v = v \cdot b / 2B$

If a third of the width of a structure is protected by barriers, accordingly only about 70% of the pressure bears on the structure. The reduction of the range of avalanches as a result of installation of obstacles can be calculated from Equations (3), (5), and (23). In and near the damming zone of avalanches small obstacles often indeed suffice to offset the thrust force of avalanches behind themselves, as for example the locomotive in front of the Dalaas rail station (see the first part of this report). Figure 29 shows how a loose snow avalanche, which fell through a forested slope without damaging the timber, lost so much energy in demolishing a brick hut that the wooden fence behind the hut remained intact, while it was destroyed on both sides thereof. The width of the intact zone is explainable by the surfaces of discontinuity spreading, with shooting flow, behind the obstacle. In the avalanche catastrophe of 1951 in Andermatt the Hotel Danioth was only slightly damaged because the ground avalanche had lost most of its energy through the prior destruction of two houses.

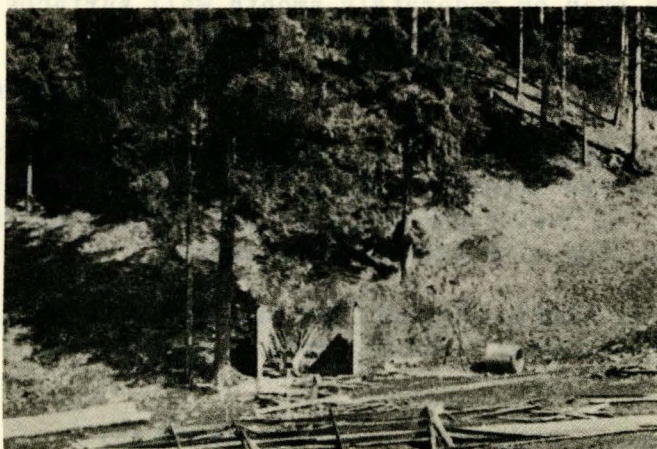


Fig. 29. Dissipation of energy of a loose snow avalanche which has fallen thru a forested slope, by the destruction of a masonry hut, behind which the wooden fence remains intact.

On the back side of a small obstacle with flow around all sides a suction up to the magnitude $\gamma_L \cdot v^2/2g \leq 1/10$ atmosphere can occur.

The suction behind obstacles around which flow occurs is usually small. The avalanche misfortune at Goppenstein in 1908 also indicated this: of 30 persons sitting together in a very lightly constructed wooden building, the 18 survived who turned their backs toward the powder avalanche which struck unexpectedly, while the 12 casualties of the avalanche had turned their faces toward it and had suffocated [3, No. 2] .

The upward pressure and thrust effects are a result of the snow movements accompanying damming; they can take effect vertically as well as in random side directions. Immediately upon impact the snow is deflected almost without loss of velocity, considering the short path length; friction likewise has only slight influence on the movement. According to Equation (24) wide avalanches at large obstacles produce the vertical damming height H times $\gamma_m / \gamma_{\max}$ (measured from the underlying surface). According to Bernoulli the vertical velocity at the height h^* over the underlying surface reaches:

$$(28) \quad u = (2g (H - h^*))^{1/2}$$

Continuity is maintained by the rolling back of the impounded snow, as is also observed in a stream of water.

The specific upward pressure on projecting surfaces (balconies, window lintels, and the like) amounts to:

$$(29) \quad p_v = \gamma_{\max} u^2/2g$$

in which $\gamma_{\max}$ is determined from Equation (22) for the impact pressure p resulting when the avalanche strikes.

In addition even on moderately smooth wall surfaces frictional forces directed vertically or inclined upwards arise:
per square meter, $R = p\mu$, in which $\mu = \gamma_{\max}/1000$ to $\gamma_{\max}/2000$.

As has been shown in the first part of the present report, the vertical forces occurring on the impact of avalanches cause a good part of the severe destructive effect of avalanches since no buildings constructed in the usual manner are able to cope with such lifting forces.

A constant or fluctuating deflection of the snow from its direction of flow by the angle δ causes a total force P acting along the angle bisector on the convex side:

$$(30) \quad P = 2 \gamma' h' (v^2/g + h'/2) \sin(\delta/2)$$

where h' denotes the flow height of the avalanche. This total pressure is

distributed on the surface of impact in such a way that the damming pressure from Equation (27) and the static damming pressure at the place being considered is nowhere exceeded. When a structure is overrun by an avalanche the weight of the damming resulting from the circumstances is to be considered as well as the frictional forces caused by the moving snow. On each side of the gradient change half of the momentum reaction given by Equation (30) is operative. The following roughly calculated data are aimed at suggesting more exact clarification of the questions touched upon.

h - height of the damming, or the depth of the snow layer
 h_0 - height of flow of the avalanche
 γ_0 - average density of the snow layer at the sliding zone
 γ - density of the flowing snow

$$(I) \quad \gamma_0 h_0 = \gamma h \quad \text{or} \quad h = \frac{\gamma_0 h_0}{\gamma}$$

Density of a snow layer is determined by the pressure of the atmosphere p_0

$$(II) \quad \gamma_0 h_0 = \gamma h \quad \text{or} \quad h = \frac{\gamma_0 h_0}{\gamma} \quad \text{according to Equation (27)}$$

γ_0 - average density for the calculation of the pressure at the maximum overpressure p in kg/m³ above the static pressure $p_0 = 10,000$ kg/m³

γ - density of the flowing snow; maximum attainable density of the snow

$$(III) \quad \gamma_{max} = \gamma_0 \left(1 + \frac{p}{p_0} \right) \quad \text{according to Equation (23)}$$

γ_{max} - maximum density after compression by the overpressure p above atmospheric pressure p_0

$\gamma_0 = 10/3$ kg/m³ - density of air

γ - density of the snow
 in the release zone

γ_u - density of the snow in the zone of destruction

α - average angle of the slope

IV. ON AVALANCHE EFFECTS AND THEIR CONTROL

1. Simplified Calculation

A. Fundamentals

Units [m = meters], [kg = kilograms], [sec = seconds]

h = vertically measured, natural snow depth, or the depth of the sliding snow layer

h' = height of flow of the avalanche

γ_0 = average density of the natural snow cover, or of the sliding snow layer

γ = density of the flowing snow

$$(I) \quad \gamma_d = \gamma (1 + p/p_0) / [1 + (\gamma p / \gamma_F p_0)] \quad \text{according to Equation (19)}$$

Density as a result of dynamic compression by the pressure p over atmospheric pressure p_0

$$(I') \quad \gamma_m = \gamma [1 + 1/2 (1 + \gamma/\gamma_F) (p/p_0)] / [1 + (\gamma p / \gamma_F p_0)]$$

according to Equation (21): $\gamma_m = (\gamma + \gamma_d) / 2$

γ_m = average density for the dynamic pressure calculation at the maximum overpressure p in kg/m^2 above the atmospheric pressure $p_0 = 10,000 \text{ kg/m}^2$

$\gamma_F = 600$ to 900 , on the average 800 kg/m^3 ; maximum attainable density of the snow

$$(II) \quad \gamma_{\max} = (\gamma_0 + \gamma_F p / p_0) / (1 + p/p_0) \quad \text{according to Equation (22)}$$

= maximum density after compression by the over pressure p above atmospheric pressure p_0

$\gamma_L \sim 10/8 \text{ kg/m}^3$ = density of air

ψ = angle of the slope

ψ_0 in the release zone

ψ_u in the zone of destruction

ψ_m average angle of the slope

$\xi \sim 400$ to 600 , on the average 500 m/sec^2

= velocity coefficient, for rough boulder terrain to grassy slopes

$\mu \sim \gamma/c$ = coefficient of friction of motion

Preliminary estimate for flowing avalanches:

$c \sim 1000$ to 2000 kg/m^2 ; for wet snow and powder snow avalanches $\mu \sim 0$.

Classification of avalanches according to Section III, 2, and [14].

B. Velocity and Flow Height

(III) $v^2 = \xi \cdot h' (1 - \gamma_L/\gamma) (\sin \psi - \mu \cos \psi)$
according to Equation (4)

a) surface avalanches and snow slabs: $h' \sim h, \gamma \sim \gamma_0$

b) powder avalanches: $\gamma = \gamma_L/2g \xi \cdot \sin \psi$

according to Equation (10)

$$h' \sim h(\gamma_0/\gamma)$$

according to Equation (9)

$$\mu \sim 0$$

as a result of this $v^2 \sim 2gh \gamma_0/\gamma_L$

according to Equation (11)

$< 2gH$ (H = vertical height of fall)

c) ground avalanches: $h' \sim 2.6 h$
(Bodenlawinen, according to Equation (16)
Grundlawinen)

$$\gamma \sim \gamma_0$$

For wet snow avalanches $\mu \sim 0$

d) distribution of velocity:

(IV) $v' = v [4/3 - (z/h')^2]$ according to Equation (26)

(1) Boundary condition: z = depth below the flow surface

(2) Boundary condition: z = distance from half the flow depth
(for powder avalanches)

e) effect of reduction of gradient from ψ_0 to ψ_u :

$$(V) \quad v_u/v_{01} = h'_0/h'_u \cong (\sin \psi_u / \sin \psi_0)^{1/3}$$

according to Equation (8)

C. Damming and Pressure Effects

Pressure head for the impact or final velocity v_u :

$$(VI) \quad H = h' + (v^2/2g) [1 - (v_u/v)^2 (1 - \sin \beta)] \quad \text{according to Equations (17) and (27)}$$

Maximum damming height:

$$H' = \gamma_m / \gamma_{\max} \quad H = p / \gamma_{\max} \quad \text{from Equation (24)}$$

β = angle between the direction of thrust and the surface impinged upon.

Horizontally measured run out distance:

$$(VII) \quad s \sim v^2 / (2g (\mu \cos \psi_u - \tan \psi_u + v^2/2 \xi h_m)) \quad \text{according to Equation (23)}$$

$$h_m \sim h' + v^2/4g$$

Specific thrust pressure

$$(VIII) \quad p = \gamma_m \cdot H \quad \text{according to Equation (25)}$$

$$\text{or } p = \gamma_F [(q/2)^2 + H p_0 / \gamma_F]^{1/2} - q/2$$

$$\text{in which } q = p_0 / \gamma - H/2 (1 + \gamma / \gamma_F)$$

$$\text{pressure distribution: } p = \gamma_m (H - h^*)$$

h^* = height of the point under consideration above the ground.

In H the velocity distribution for the place being considered can be taken into consideration using Equation (IV).

In front of small obstacles (for example poles, masts of diameter $\emptyset$) compression of snow cannot occur; from Equation (27) it is true that

$$p \sim (\pi \emptyset / 4) (\gamma v^2 / 2g) \quad \text{kg/m}$$

$$(IX) \quad P_V = \Sigma p \cdot F_H + \Sigma \mu \cdot p \cdot F_V \sim \mu^* \cdot p \cdot F_V^*$$

= upward force on the part of the surface F_H dammed under (see above) and lying in the flow direction and the friction force on the surface struck F_V , both forces acting in the possible direction of the damming of the snow or of flowing off of the snow. For normal facade walls of total area F_V^* , in considering upward force and friction, one can set, on the average, $\mu^* = 0.3$. In

terrain that falls away steeply, downward acting thrust and frictional forces can occur, depending upon the possibilities for the compression and flowing off of the snow.

The total dynamic thrust on a horizontal roof overrun by an avalanche is, per meter of width:

$$(X) \quad P = \gamma h' \left(h'/2 + v^2/g \right) \tan(\psi_u/2)$$

The pressure distribution is such that the specific damming pressure γ times $v^2 \sin \psi_u / 2g$ is not exceeded. In addition the specific static pressure $\gamma h'_u$ and the specific frictional force $\mu \cdot \gamma \cdot h'_u$ are acting.

2. Calculation of Individual Situations

A. Blons and Sonntag (see Section I, 2A)

a) Powder avalanche, without whirling up the lower snow layer

$$h = 1.6 \text{ m}, \quad \gamma_0 = 150 \text{ kg/m}^3, \quad \psi_m \sim 30^\circ$$

$$\text{From Eq. (III, 10): } \gamma = 15.6 \text{ kg/m}^3$$

$$(III, 9): h' = 15.4 \text{ m}$$

$$(III, 11): v = 62 \text{ m/sec}$$

$$(VI): H = 205 \text{ m}$$

$$(VIII): p = 3800 \text{ kg/m}^2$$

$$(\text{local determination: } p = 3000 \text{ to } 5000 \text{ kg/m}^2)$$

$$(II): \gamma_{\max} = 330 \text{ kg/m}^3$$

$$(VI): H' = 11 \text{ m}$$

$$(IX): p_V = 570 \text{ kg/m}^2$$

Average for the facade up to a height of 6.5 m above ground

$$p_V = 800 \text{ kg/m}^2$$

$$(\text{local determination: } p_V = 650 \text{ to } 800 \text{ kg/m}^2)$$

b) Esch Gulch avalanche (Bodenlawine)

$$h = 1.6 \text{ m}, \quad \gamma_0 = 150 \text{ kg/m}^3, \quad \psi_m \sim 30^\circ, \quad \mu = \gamma_0/1000,$$

$$\beta = 60^\circ$$

$$\text{Eq. (III, 16): } h' = 4.15 \text{ m}$$

$$\text{(III)}: v = 27.5 \text{ m/sec}$$

$$\text{(VI)}: H = 38.5 \text{ m}$$

$$\text{(VIII)}: p = 7350 \text{ kg/m}^2$$

(local determination from Section I, 2, A, d: $p > 6000 \text{ kg/m}^2$)

B. Surface Avalanche at Dalaas

The fact that the railroad train struck by the avalanche was able to protect the portion of the building standing behind it proves the small flow height of the avalanche. Under the existing snow conditions (Section I) it could only have been a surface avalanche.

$h = 1.6 \text{ m}$, $\gamma_0 = 150 \text{ kg/m}^3$, longitudinal profile as in Figure 2.

In the release zone $\psi_0 = 45^\circ$, in the zone of destruction $\psi\mu = 130^\circ$, for surface avalanches $\mu \sim \gamma_0/2000$

$$\text{Eq. (III, a) and (V): } h_u = 2.35 \text{ m}$$

$$\text{(III)}: v = 13.5 \text{ m/sec}$$

$$\text{(VI)}: H = 11.3 \text{ m}$$

$$\text{(VIII)}: p = 1800 \text{ kg/m}^2$$

(local determination from Section I, 2, B:

$p = 1200 \text{ to } 2400 \text{ kg/m}^2$)

$$\text{(II)}: \gamma_{\max} = 250 \text{ kg/m}^3$$

$$\text{(VI)}: H' = 7.3 \text{ m}$$

(local determination from Section I, 2, B:

$H' \sim 7 \text{ m}$)

The upward force of the snow (Figure 12) which had entered through the windows and doors of the ground floor areas acted upon a total horizontal surface of size similar to the facade area which had been struck; the average upward pressure per square meter of the facade surface struck reached according to Equation (X), $p_v = p/2 = 900 \text{ kg/m}^2$ (local observations: $p_v = 500 \text{ to } 1000 \text{ kg/m}^2$).

In the area of the railroad with inclined terraces, ditches, tracks clear of snow, etc., the mean coefficient of ground friction will reach approximately

$\mu = 1/5$. According to Equation (VII) in this case the runout distance in the horizontal area of the rail station free from obstacles will be $s \sim 45$ m. After impact of the avalanche on the train it must have dammed up until the tipping force (850 kg/m^2 for the locomotive) was generated, and in so doing, according to Equation (17), its velocity was reduced from 13.5 to 9 m/sec. Before the impact the kinetic energy per cubic meter of avalanche snow amounted to $\gamma \cdot v^2 / 2g = 1350 \text{ kg-m/m}^3$; overturning the locomotive consumed the kinetic energy of about 20 m^3 of avalanche snow. The damming produced in this way also caused a reduction in velocity of the following avalanche snow of the order of magnitude indicated above. To push forward the overturned locomotive a pressure of about 400 kg/m^2 is necessary according to Section I. From the momentum equation $p = \gamma/g (v \Delta v)$ the velocity loss brought about in this manner is $\Delta v = 3.3 \text{ m/sec}$.

For the remaining velocity of 5.7 m/sec Equation (VII), with $\mu = 1/5$, gives the run out distance $s \sim 8$ m. The above calculated results are in agreement with the observations (Section I).

C. Swiss Experience

Taking everything into consideration, investigation of the utilizeable data from the 1951 catastrophe leads to forces of a similar order of magnitude to those which have been established in the 1954 catastrophe in the Vorarlberg (see Section I). For this reason in the following only a few typical situations are discussed in more detail which reveal the effect of significantly greater forces or which make possible a check of particular calculations.

A difference exists compared with the circumstances in the Vorarlberg; in the Swiss catastrophies, the terrain, after a relatively short slope of slight inclination, usually climbed through a steep, partly rocky zone, up to the usually high lying release zone. The steep avalanche paths often caused important, downward acting thrust forces [see the comment on Equation (IX)]; this has been observed for example at Vals and Andermatt.

a) Andermatt 1951 [11]

Concerning the surface avalanche which ran from the Kirchberg zone of defense structures.

$$h = 2.2 \text{ m}, \gamma = 150 \text{ kg/m}^3, \psi_o = 34^\circ, \psi_m = 24^\circ,$$

$$\text{slope of the valley floor} \sim 5\% (\psi_u \sim 3^\circ), \mu = \gamma/2000$$

$$\text{Eq. (V)}: h_u = 2.45 \text{ m}$$

$$\text{(III)}: v = 20.5 \text{ m/sec}$$

$$\text{(VIII)}: p = 4000 \text{ kg/m}^2$$

$$\text{(27')}: \text{Pressure on telephone poles 20 cm in diameter}$$

$$P = 625 \text{ kg/m}$$

$$\text{Bending moment } M = P h_u^2 / 2 = 1900 \text{ kg-m}$$

$$\text{Stress } \sigma = M/W = 240 \text{ kg/cm}^2$$

$$(VII): \quad \text{Run out distance } s = 380 \text{ m}$$

Local observations [11]; Although the telephone poles standing in the avalanche path remained intact for the most part (the breaking stress of about 400 kg/cm^2 was not reached,) debris from the destroyed structures was carried as much as 350 m onto the valley plain.

b) Break of the suspension tower on the 50 kv transmission line between Davos and Filizur in January 1951 [15].

Constructed according to plans MC (9706/82); tower height 19 m. Angle between the avalanche's direction of action and the transmission cable $\psi_s \sim 30^\circ$. Natural new snow height $h = 1 \text{ m}$; $\gamma_o = 200 \text{ kg/m}^3$. Release zone gradient 30%; gradient in the zone of destruction 20%.

$$\text{Eq. (III, b): } \gamma_u = 6 \text{ kg/m}^3, h_u = 33 \text{ m}$$

$$(III)): \quad v = 56.5 \text{ m/sec}$$

The snow pressure of the powder avalanche acted upon the entire tower height. Thrust on the four steel tubes of 10 cm diameter, taking into consideration the velocity distribution according to Equation (IV):

$$P = 4(\pi d/4) (\gamma v^2/2g) = 300 \text{ kg/m}$$

Moment from the snow pressure $M = 50,000 \text{ kg-m}$

Moment in the longitudinal direction of the avalanche $M \cdot \cos \beta = 44,000 \text{ kg-m}$

Verification from the construction: The tower constructed with a factor of safety of about 2.5 for normal stresses, showed a mathematical breaking moment of about 20,000 kg-m, referred to the mast footings. The breaking load was exceeded by the thrust of the avalanche by about a factor of two.

c) Avalanche accident at Zuoz 1951 [15]

$$h = 1.23 \text{ m}; \gamma_o = 282 \text{ kg/m}^3, \psi_m = 24^\circ$$

In the release zone $\psi_o = 29^\circ$, at the valley floor

$$\psi_u = 10^\circ \text{ ascending (average value)}$$

Mixed surface and powder avalanche:

$$\text{Eq. (III, 10): } \gamma = 15 \text{ kg/m}^3$$

$$(III, 9): \quad h' = 23 \text{ m}$$

$$(V)): \quad h_u = 24.5 \text{ m}$$

$$\text{Eq. (III, 11): } v = 75 \text{ m/sec}$$

$$\text{(VI): } H = 302 \text{ m}$$

$$\text{(VIII): } p = 5800 \text{ kg/m}^2$$

The construction plans of a destroyed, massive stone house permit one to conclude that the breaking load was about 5000 kg/m^2 .

$$\text{Eq. (VII): } s \sim 1300 \text{ m}$$

The powder avalanche crossed the valley floor and reached approximately the foot of the opposite slope. The extent of the more dense avalanche core was smaller and was retarded in addition by the obstacles struck.

d) Forest Avalanche at Glaris 1951 [11]

At Glaris a loose snow avalanche trickled down through an initially steep ($\psi_0 = 36^\circ$) forested slope and, in less steep ($\psi = 15$ to 25°) forested terrain lying below, for the first time broke or overturned spruce trees with a trunk diameter up to 15 cm. In spite of this weak effect the avalanche still destroyed a barn in the flat meadow about 100 m from the edge of the forest.

These phenomena are explainable by a new snow layer ($\sim 0.5 \text{ m}$) flowing down with small energy and subsequent formation of a small powder avalanche. Equations (III): (9) and (10), yield larger densities and smaller flow heights for steeper slopes, while from Equation (III): (11) the velocity remains constant. Assuming a new-snow density of 50 to 100 kg/m^3 it can be shown from Equation (VIII) that on the initial steep slope no trees were destroyed while this did occur on the less steep timbered slope adjoining below. The velocity loss from the resistance of a row of trees of diameter d and spaced at an interval a , from the momentum equation

$$P = (m/\Delta t) \Delta v$$

combined with Equation (27')

$$(\gamma v^2/2g) (\pi d/4) h' = a h' v (\gamma/g) \Delta v$$

is

$$\Delta v = (\pi d/8a) v$$

After traveling through n rows of trees the velocity still amounts to

$$v_u = (1 - \pi d/8a)^n v$$

For example, the velocity after traveling through 100 rows of trees 15 cm average diameter and spaced at 3 m intervals lengthwise and crosswise still amounts to about $1/6$ of the original velocity. A small impact velocity is sufficient to destroy a barn; the extent of powder avalanches in flat terrain is very large according to Equation (VII):

e) Powder avalanche at Mauvoisin (see Fig. A)

In February 1954 a snow cover of 1.7 m depth and about 100 kg/m³ average density lay at Mauvoisin. At about 2500 m above sea level an avalanche released, formed a powder avalanche on a rock slope with an average inclination $\psi_0 = 47^\circ$ and after striking the bottom of the relatively narrow gorge (valley floor 1740 m above sea level) was propelled upward on the opposite slope with an average inclination $\psi_u = 36^\circ$ to a height of 1960 m above sea level.

According to Equation (III, 11) the maximum velocity was 53 m/sec. The horizontally measured run out distance according to Equation (VII) is: $s = 170$ m. The powder avalanche thus climbed on the opposite slope to a height $s \cdot \tan \psi_u = 120$ m above the valley floor; the uppermost part of the powder avalanche reached the damming height $v^2/2g = 140$ m higher. Consequently the calculated total height of the powder snow cloud reached 260 m, i. e., it reached at the highest point the 2000 m contour line, which agrees approximately with observation. Powder avalanches are, in the limiting region of the highest damming as a result of the dissipation of the kinetic energy, relatively harmless.

f) Snow pressure measurements on an impact plate (SFL)

Terrain gradient: $\psi_0 = 45 - 50^\circ$, $\psi = 24^\circ$

Wet snow : $\gamma_0 = 400$ kg/m³, $\mu \sim 0$, $h = 0.7$ m

Equation (III) : $v = 22$ m/sec

Equation (VIII) : $p = 12,000$ kg/m²

Measured maximum pressure: $p = 11,825$ kg/m²

g) Experience with supporting structures (avalanche defense structures)

Of the countless structures which have been exposed to the pressure of snow, three supporting structures, constructed with various materials according to the prevailing hypothesis of the load, which suffered exceptional damage and which permit an estimate of the loads experienced owing to their statically determinable construction for a factor of safety of 2 or 3, are referred to here. The new snow ($\gamma_0 \sim 200$ kg/m³), ($\mu \sim \gamma_0/2000$) lay 1.5 m deep. After the damages had been sustained snow slab fractures were determined to have occurred about 50 m above the structures; in the first instance the fracture was 50 cm high, in the second 1 m high and in the third case snow drifts up to 10 m in height lay above the structure concerned.

(1) Supporting structure constructed for a snow pressure of 1.2 t/m² with a structure height $d_0 = 3$ m, measured perpendicular to the 65 to 70% slope

Snow slab of 1/2 m flow height

Eq. (III) : $v = 11$ m/sec

$$\text{Eq. (VIII): } p = 1.4 \text{ t/m}^2$$

Surface avalanche of 1.5 m flow height

$$\text{Eq. (III): } v = 20 \text{ m/sec}$$

$$\text{Eq. (VIII): } p = 4.5 \text{ t/m}^2$$

From Equations (3) and (5) it can be shown that the initial running distance of 50 m is sufficient to reach the above velocities.

(2) Supporting structure constructed for a snow pressure of 3.4 t/m^2 with a structure height $d_0 = 2.5 \text{ m}$, measured perpendicular to the 80% slope.

Snow slab of 1 m flow height

$$\text{Eq. (III): } v = 16.5 \text{ m/sec}$$

$$\text{Eq. (VIII): } p = 3 \text{ t/m}^2$$

Surface avalanche of 1.5 m flow height

$$\text{Eq. (III): } v = 21 \text{ m/sec}$$

$$\text{Eq. (VIII): } p = 5 \text{ t/m}^2$$

(3) Supporting structure constructed for a snow pressure of 1.9 t/m^2 with a structure height $d_0 = 3 \text{ m}$, measured perpendicular to the 60 - 80% slope. The structure gave way because extraordinary snow depths caused the static creep pressure to exceed that for which the structure was designed. The formation of the extensive snow drifts, up to 10 m in depth, was probably favored by the structures; they had never been observed in this place previously.

The maximum creep pressure [16] for $d = 3 \text{ m}$, $\gamma_0 = 400 \text{ kg/m}^3$, pressure concentration factor $k = 3$ for edge elements:

$$p_{\max} \sim k \cdot \gamma_0 : d \cdot \sin\psi = 1.8 \text{ t/m}^2$$

with $h = 10 \text{ m}$:

$$p_{\max \max} \sim k \gamma_0 h \sin\psi \cos\psi \sim 5.2 \text{ t/m}^2$$

The creep pressure can in no case exceed the upper boundary value of the Rankin stress state; this has been determined [17] for the last mentioned case to be $p_{\max} = 6 \text{ t/m}^2$, assuming an angle of repose $\psi_0 \sim 30^\circ$.

After reaching the boundary condition the snow begins to dam up in front of the supporting wall and can exert upward directed forces upon it. Creep is nothing other than a very slow laminar flow.

In all the situations discussed above the action of a tensile force in the upper main beams of the obstruction supports was observed as evidenced by the lifting of the foundations on the side toward the mountains and their displacement. These upward directed forces are understandable as the results of the upward pressure from the impact of small snow slides (Equation IX); however in the third situation they also occur for static reasons as a result of creep pressure.

It was not possible to procure all the details with the desired completeness for the examples discussed; however the calculations show that the interrelations established are not to be doubted and may serve as a suggestion for additional evaluations of avalanche observations.

3. Conclusions for Protective Designs

A. The research described enables the essential systematic compilation of additional experimental data, especially about flow and frictional resistance to avalanches under varying weather, snow, and ground conditions. The simplified Equations (I) through (X) allow, in view of the evidence furnished, a suitable assessment of the effects of avalanches to which structures are exposed under given conditions and thereby the construction of sufficiently avalanche-proof new structures and protective structures. Reinforcement of existing building structure, especially to absorb the forces directed upwards, can considerably improve safety in avalanche imperiled territory. Along with the impact effect of avalanches, as a rule important upward force components occur in accordance with Equation (IX). Above all, for structures of any kind, the resistance to avalanche effects in each case is dependent upon their adequate resistance to tipping, which, in turn, depending upon the system of construction, requires anchorings at the building site on the side towards the mountain. For the permanence of any protective structures an adequate means of diverting the surface melt water and seepage is important.

B. The construction elements of avalanche-proof protective and new structures must resist the impact load of the avalanche snow given by Equations (VIII) and (X). Data for the snow heights and densities to take as a basis for a calculation are to be found in the SLF Reports [1].

As a rule for

Formation of powder and surface avalanches:	New snow depth	> 1 m
Dangerous powder and surface avalanches:	New snow depth	> 3/2 m
Danger of ground avalanches (Grundlawinen):	Settled snow	> 1/2 m
Danger of a catastrophic avalanche:	New snow depth	> 5/2 m
	Settled snow	> 1 m

and for

Powder avalanches:	γ_0 up to 200 kg/m ³
--------------------	--

Surface avalanches: γ_0 up to 300 kg/m³

Ground avalanches (Bodenlawinen): γ_0 up to 400 kg/m³

Since avalanche paths frequently deviate from the steepest fall line, protective structures and obstructions must have sufficient lateral rigidity.

Construction elements with large fracture strengths or large mass best resist the local impact stresses of debris entrained in the avalanche snow, rock fall, or rolling snow. Pieces of debris become carried along in an avalanche as soon as the thrust force of the avalanche snow, taking into consideration the upward pressure, is sufficient to repeatedly overturn the fragment or stone. Avalanche snow of density γ and velocity v overturns a prismatic stone of density γ_1 , ground area $a \cdot b$, and height c as soon as

$$v^2 > 2g (b^2/c) [(\gamma_1/\gamma) - 1]$$

where b is the width, i. e., the smallest dimension of the ground area. The stone is raised by the upward pressure as soon as

$$v^2 > 2gc [(\gamma_1/\gamma) - 1]$$

where c is the smallest dimension of the piece. The work expended in entrainment of debris can be neglected as a rule, i. e., the velocity of the fragments can be set equal to the flow velocity of the avalanche. The EMPA Report No. 136 contains data [18] concerning the impact requirements of construction which also can serve to estimate the effect of rock fall. The velocity of a rock rolling down the slope or of a snow ball rolling down, from equating kinetic and potential energy, is:

$$v = 0.845 (2 g H^*)^{1/2}$$

in which H^* is the total height of fall measured vertically. Sliding can occur if $\tan \psi > 3.5\mu$. The velocity is independent of the size and material of the ball rolling down. The maximum impact pressure of a snow ball of diameter $\emptyset$ and density γ can be estimated from the momentum equation for loss in velocity over intervals:

$$P dt = (\pi \emptyset^2/4) (\gamma/g) v dt \Delta v$$

and since dt can be chosen as small as desired:

$$P_{\max} \sim (\pi \emptyset^2/4) (\gamma/g) v^2$$

By way of example a maximum impact of 6 to 7 t occurs when a snow ball with a $\emptyset \sim 1$ m strikes the obstruction described in Section IV, 2 g, from a distance of 50 m on a 60 - 80% slope.

C. Wedge shaped bulkheads constructed directly in front of the structure to be protected are most effective against all kinds of avalanches; their height is selected tall enough and their wedge angle 2β small enough that the damming

of avalanche snow according to Equation VI can no longer inundate the protected object. The protective action against powder avalanches is to be surveyed taking into consideration the lateral spreading velocity and the mechanics of the trajectory of free streams. At times powder avalanches deposit much snow immediately behind protective structures by eddy action without a large pressure effect. The wing walls of the wedge-shaped bulk head must be sufficiently long to correspond to the lateral spreading velocity of the avalanche given by Equations (1) and (2). Such wedge-shaped bulk heads have stood the test of existing experience as long as they were built high enough [1, 3, 5]. The wedge-shaped barriers can be built smaller if their protective action is confined to the ground floor, whose roof must then hold out against the possibility of being overrun by an avalanche. For the protection of persons on public thoroughfares, mountainside protective niches located sufficiently nearby are advisable.

D. Diversion walls and deflectors of satisfactory height, arranged at a considerable distance from the objects to be defended, protect against ground and surface avalanches only to a limited degree; after snow fills in behind these defense structures their effectiveness in causing a loss in velocity is greatly diminished, as the catastrophe at Airolo has shown. Nevertheless the striking of a free stream upon a horizontal surface always causes a distribution of the vertical velocity component and the plastic compressibility of specific kinds of snow causes, with each damming or deflection of the avalanche, significant losses in energy, which can be estimated with the aid of Equations (I) and (II). The kinetic energy of avalanche snow is equal to the damming pressure $p_s = \gamma v^2/2g$ kg-m/m³; with a deflection of the avalanche over the angle β the pressure occurring there is $p \sim p_s \sin \beta$. If the snow had a density γ_0 before the deflection then this is increased by p to the density γ_d , which is maintained by a sufficiently long action of p . The permanent compression work amounts to:

$$p \, dV \sim p (1 - \gamma_0 / \gamma_d) \text{ in kg-m/m}^3$$

and the decrease in the kinetic energy per cubic meter of snow is $p \, dV$. The velocity v_1 after the deflection is:

$$\gamma v_1^2/2g = p_s - p \, dV$$

Dynamic experiments are necessary to check the time dependent compression law. Oriented experimental tests have already indicated that considerable energy losses occur when avalanches overrun terraces of sufficient size and number (see also Equation VI).

Experience confirms the universal postulate of the momentum theorem: No energy loss occurs without the absorption of force--and conversely.

The deflection of an avalanche by diversion walls is more reliable the smaller the angle between them and the flow direction of the avalanche. Short, staggered, buffer walls arranged in series are more effective than a wall of great length built at right angles to the avalanche path, since uniform flow movement of the avalanche is prevented in this way. In so doing, the total length of the structure can be reduced and this saving is usefully transferred into

greater height and strength of the individual structures, so far as the technical aspects alone are concerned.

E. Wedge-shaped buffers are stressed less, but also are less effective than buffer walls arranged at right angles to the avalanche path. All of these buffer structures are ineffective in protecting the structures lying below against powder avalanches. Experience indicates in this regard that an insufficient size of the structures cannot be outweighed by greater numbers of them, whether it is a matter of buffer and diversion structures or of obstructions in the release zone. If the latter are not high enough to prevent the formation of surface avalanches, they can cause avalanches [19], especially if they favor the formation of higher snow drifts in their vicinity.

Defense structures in the release zone of avalanches have given heretofore no certain protection against the formation of avalanches in their area, since earlier they were usually constructed too low and too wide [1], [3]. However, modern obstructions have generally stood the test in recent periods of catastrophe.

The observations described in Section IV, 2, show that indeed small snow slides can exert considerable dynamic impact and lifting forces on obstructions [Equations (3), (5), (VIII), (IX)]. Also the creep pressure, in its final state after reaching the upper limiting value for equilibrium by side thrust, can acquire fundamentally upward directed components, which to be sure cannot as yet be measured but can probably be observed [16]. It is, at the very least, not advisable to base the margin of safety of static calculations on a downward acting component of creep pressure. Without exception up to now damage observed to supporting structures of various kinds and of various materials was caused primarily by lifting and shifting of the foundation on the side toward the mountain. A substantial increase in the margin of safety is to be expected by connecting the mountain side foundation of the post beam and the valley side foundation of the support by means of a tie rod. In special cases, which exceed the range of validity of creep research up to now [6], [7], the maximum possible creep pressure can be estimated by the methods of calculating passive soil pressure [17], [20]. The spacing of individual units of constructions is limited by the requirement that an angle of repose ϕ between the snow and the ground ought not be exceeded. This corresponds to a slope inclination of $\psi_R \sim \phi \sim 25^\circ$, below which no avalanche releases have yet been observed. Exceeding the angle of repose will cause greater slip movement of snow, which can lead, in the course of creep, to exceeding the limiting value for the internal equilibrium of the snow and to damming of the same in front of the supporting structure. This brings to play dangerous upward directed forces. If the supporting structure, set approximately perpendicular to the slope, is rated for the creep pressure $K \text{ kg/m}^2$ of snow density $\gamma_{\max} \text{ kg/m}^3$ with a factor of safety n , the spacing L of the individual units may not, from the above requirement and geometrical considerations of equilibrium, exceed the following value:

$$L < (Kn / \gamma_{\max}) (\cos \phi / \sin(\gamma - \phi))$$

If L is chosen larger, greater forces must be absorbed.

Also the uppermost structure should have, at most, a spacing L from a

flattening of the terrain lying above (ridge crest or terrace with $\psi_R \sim \varphi$).

With increasing interval between the structures their possible load increases; it can reach its breaking load $K \cdot n$ with the above maximum spacing L . For the infrequently attained maximum load a factor of safety of n times is also provided, so this factor n is omitted in the formula above.

It is not only an economic question whether the overloading of structures established in this report is to be considered in the case of dimensioning. Indeed such overloads seldom occur, but hardly less infrequently than the coincidence of unfavorable snow and weather conditions, which, from time to time in following decades will lead to a typical catastrophic situation against which obstructions and defense structures will have to stand up some day.



Fig. 30. Snow layer pushed onto picket fences. In the foreground and background a snow layer has slid off down to the grass.

The investigations published in the present article were vitally expedited by the data of the Federal Forest Inspectorate and the forest inspectors of the cantons of Graubunden and St. Gallen as well as the Section for Torrent and Avalanche Control, Vorarlberg (Councillor Wagner and Forest Engineer Brantner). In addition, the collaboration of the S. L. F. (meteorological data of Dr. Th. Zingg and evaluation of the measurements of Dr. M. Oechslin by Engineer A. Roch), graciously permitted by Dr. de Quervain, was of great value.



Fig. 31. Beginning of the formation of an avalanche in wet snow: Creep -- Fracture -- laminar flow. Mittelgrat above Davos.

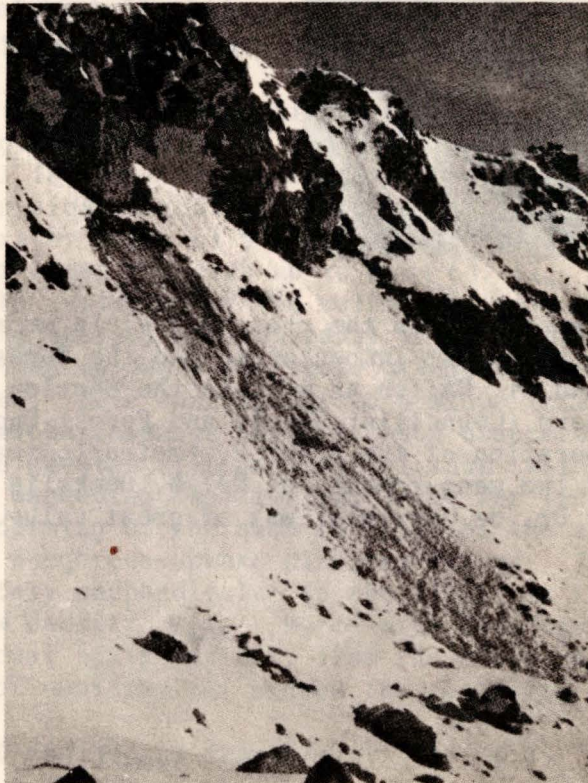


Fig. 32. Continued development of the avalanche in the process of formation in Fig. 31: Laminar flow -- Formation of blocks -- Turbulent motion. Mittelgrat above Davos.

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